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[*Continued on page (III) of Cover*

THE TWENTY-EIGHTH KELVIN LECTURE
"THE ELEMENTARY PARTICLES OF MATTER"

By PROF. J. CHADWICK, M.Sc., Ph.D., F.R.S.

(*Lecture delivered before* THE INSTITUTION, 22*nd April*, 1937.)

The work of Kelvin illuminated all branches of pure and applied physics and included many of the most important discoveries of his time. Yet on the occasion of the celebrations in honour of his fiftieth year as professor of natural philosophy in the University of Glasgow he spoke these words: "One word characterizes the most strenuous of the efforts for the advancement of science that I have made perseveringly during 55 years; that word is *failure*. I know no more of electric and magnetic force, or of the relation between ether, electricity, and ponderable matter, or of chemical affinity, than I knew and tried to teach to my students of natural philosophy 50 years ago in my first session as professor."

These words emphasize in a startling way Kelvin's conviction that the ultimate problem of natural philosophy was the dynamical theory of matter, and his unsatisfied longing to see the solution of this problem. Connections between different physical phenomena had been gradually brought to view during his boyhood; the chemical actions of the electric current, the magnetic properties of the current and the generation of current by a moving magnet, the effect of a magnetic field on light, etc. Some of his early papers and notebooks show that he felt compelled to find relations between electricity and magnetism and mechanical properties. He seems to have been specially impressed by the necessity of finding an explanation of the electrical properties of matter. In his Presidential Address to the Royal Society in 1893 he said "Fifty years ago it became strongly impressed on my mind that the difference of quality between vitreous and resinous electricity . . . must be studied if we are to learn anything of the nature of electricity and its place among the properties of matter."

"Tell me what electricity is," he said to Tait about 1862, "and I will tell you everything else." Later, after Maxwell had developed his electromagnetic theory of light, Tait invited Kelvin to fulfil his promise. But Kelvin could not be satisfied with Maxwell's ideas alone, partly perhaps because he could not make a dynamical model to illustrate the equations, but partly because Maxwell's theory was not founded on molecular dynamics. What Kelvin wanted was a comprehensive theory which would explain all the properties of matter in terms of its structure. "All the properties of matter are so connected that we can scarcely imagine one thoroughly explained without our seeing its relation to all." Again and again he returned to the consideration of this problem, as new suggestions and methods of approach—"finger-posts," as he called them, "which may lead to a full understanding of the properties of matter"—occurred to him. His Address to The Institution as its first President was entitled "Ether, Electricity, and Ponderable Matter."* He wrote, in a letter to the Secretary, "I shall have to state very strongly that the difficulties in the way of proving a comprehensive dynamical theory of electricity, magnetism, and light are quite stupendous; and that in the present state of science the imagination is absolutely baffled in attempts to give a mechanical foundation for explaining great laws of nature on which the work of the electrical engineer depends."

A few years later, in his Address to the Royal Society, he drew attention to the experiments on the passage of electricity through rarefied gases. He pointed out that Cromwell Varley, as long ago as 1871, had provided "an important first instalment of discovery in a new field—the molecular torrent from the negative pole, the control of its course by a magnet. . . ." Then, after discussing the work of Crookes on this subject and supporting the view that the cathode stream consisted of particles, he said "If a first step towards understanding the relations between ether and ponderable matter is to be made, it seems to me that the most hopeful foundation for it is knowledge derived from experiment on electricity in high vacuum."

Two years after this address there came Röntgen's discovery of the new rays generated by the impact of the cathode torrent on a target, followed a short time later by the discovery by J. J. Thomson, and independently by Wiechert in Germany, that the particles in the cathode stream were not molecules but particles of very much smaller mass.

It was shown by J. J. Thomson that these carriers of negative electricity were of the same type, i.e. had the same ratio of charge to mass, e/m, whatever the chemical nature of the gas or cathode material in the discharge tube; and later that the same particles were liberated from solids raised to a very high temperature or exposed to ultra-violet radiation. He concluded, therefore, that these particles, which we now call electrons, were common constituents of all atoms of matter. Subsequently the magnitude of the charge on a gaseous ion was measured and then the mass (m) of the electron could be calculated from the ratio e/m. The mass of the electron is 1 840 times smaller than the mass of the hydrogen atom, and its charge is $4 \cdot 8 \times 10^{-10}$ e.s.u.

These experiments not only gave us the first of the units from which all matter is built up but they suggested that the smallest possible unit of negative electric charge was that carried by the electron, i.e. that electricity is also atomic in structure and that the electronic charge is the fundamental unit. Moreover, since a charged particle possesses inertia or mass simply in virtue of the magnetic field set up when it moves, it

* *Journal I.E.E.*, 1889, vol. 18, p. 4.

appeared possible that the mass of the electron might be wholly of electromagnetic origin.

In this way came the first great advance towards a comprehensive theory of the structure of matter and the relation between electricity and matter so long desired by Kelvin. The electron theory gave immediately the explanation of the phenomena of electrolysis and of the ionization of gases; it provided a fairly satisfactory interpretation of the thermo-electric and photo-electric effects, though the applications to the interpretation of chemical forces and of the conduction of electricity in metals, while suggestive, were not very successful.

As far as the structure of the atom was concerned, it was agreed that only a very small fraction of the mass of an atom could be associated with electrons. J. J. Thomson showed, from experiments on the scattering of X-rays, that the number of electrons contained in an atom was roughly about half the value of the chemical atomic weight of the atom. Speculation about the positive electricity of the atom was vague; it was generally supposed that the positive electricity, in amount to balance the negative charge of the electrons, was distributed over the whole volume of the atom.

Now about the same time as the discovery of the electron, Becquerel had discovered the phenomenon of radioactivity. It was shown by Rutherford and Soddy that radioactivity was the manifestation of the spontaneous breaking-up of an atom with the emission of a radiation and the formation of a new atom. In some cases the radiation consisted of fast-moving electrons, called β-particles, in other cases of α-particles. The latter were shown to be positively-charged atoms of helium, which thus appeared to play a part in the structure of heavy atoms. But for our present purpose the great importance of the α-particle arises from the fact that it is shot out of the radioactive atom with great speed. The α-particle is an electrically charged projectile of enormous energy and momentum, and very large forces would be necessary to turn it from a rectilinear path. Nevertheless, when α-particles are passed through matter some of them occasionally undergo an abrupt deflection through a relatively large angle, as illustrated in Fig. 1 (see Plate 1, facing page 698). Rutherford showed that such deflections could only be explained if there were a very strong electric field within an atom, and that this field must be associated with the mass of the atom. He therefore suggested that the atom consists of a very small nucleus carrying all the positive charge of the atom and all the mass (except for the electrons), surrounded by a distribution of electrons, in number to make the atom electrically neutral. This nuclear theory of the atom is a landmark in the history of physics. It pointed the way to all subsequent developments and made possible the extraordinarily rapid advance of recent years.

On this theory the physical and chemical properties of the atom depend on the number and arrangement of the electrons. These are both determined by the positive charge on the nucleus. Thus the magnitude of the nuclear charge is the most important characteristic of an atom. It was suggested by van den Broek, and proved by the experiments of Moseley, that the magnitude of this charge is determined by the number of the place of the element in the periodic table—the " atomic number " of the element. This atomic number gives the number of electronic units of charge on the positive nucleus or the number of electrons in the atom outside the nucleus. The clue to the arrangement of the electrons was provided by Bohr, who showed, on the basis of the quantum theory, that the optical spectra emitted by an atom could be interpreted to give the electronic structure of the atom. The further developments of the quantum theory have led to a new atomic mechanics which provides a complete interpretation of most of the ordinary physical properties of matter. Dirac writes in his book " Quantum Mechanics ": " The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble."

This achievement of modern physical theory would meet many of Kelvin's wishes. Nearly all the physical phenomena known at his time come within the scope of Dirac's statement, and we can give " a mechanical foundation for explaining great laws of nature on which the work of the electrical engineer depends."

But the investigation of atoms revealed new phenomena and problems, above all the problem of the structure of the atomic nuclei. There are 92 chemical elements and, taking the isotopes into account, there are more than 300 varieties of nucleus. Must we have a special individual particle for each, or can we build up all the varieties from a small number of elementary particles? The simplest nucleus is the nucleus of the atom of hydrogen, which has one unit of positive charge to balance the charge of the one electron of the external structure. On the chemical scale of atomic weights, the mass of the hydrogen nucleus is 1 (approximately), while the mass of every other nucleus is almost exactly a whole number. It is therefore natural to assume that the hydrogen nucleus, given the name " proton " by Rutherford, is a unit in the structure of all nuclei. If, in addition, we assume that the atomic nuclei contain electrons, in order to give them their appropriate charges as well as masses, we have a picture of all matter built up from two elementary particles, the proton and the electron. Thus an atom of atomic weight A, and atomic number Z, will have Z electrons in the external structure; its nucleus will contain A protons and $(A-Z)$ electrons. Support for this view was provided from the phenomena of radioactivity, where electrons are known to be emitted from the nucleus, and of the artificial disintegration of light elements, where the capture of an α-particle by the nucleus results in the emission of a proton (see Fig. 2).

But certain difficulties began to appear. To describe one of these difficulties I must begin by relating the characteristic properties which define a particle. I have already mentioned two of these properties—the mass and the charge. A third characteristic property is the angular momentum, which is an invariant property of elementary particles according to quantum mechanics.* It is known that both the electron and the proton have an angular momentum, commonly called " spin," of $\frac{1}{2}$ in

* If the particle has a charge it may also have magnetic moment, for the charge rotating about an axis is equivalent to a system of circular currents.

Plate 1

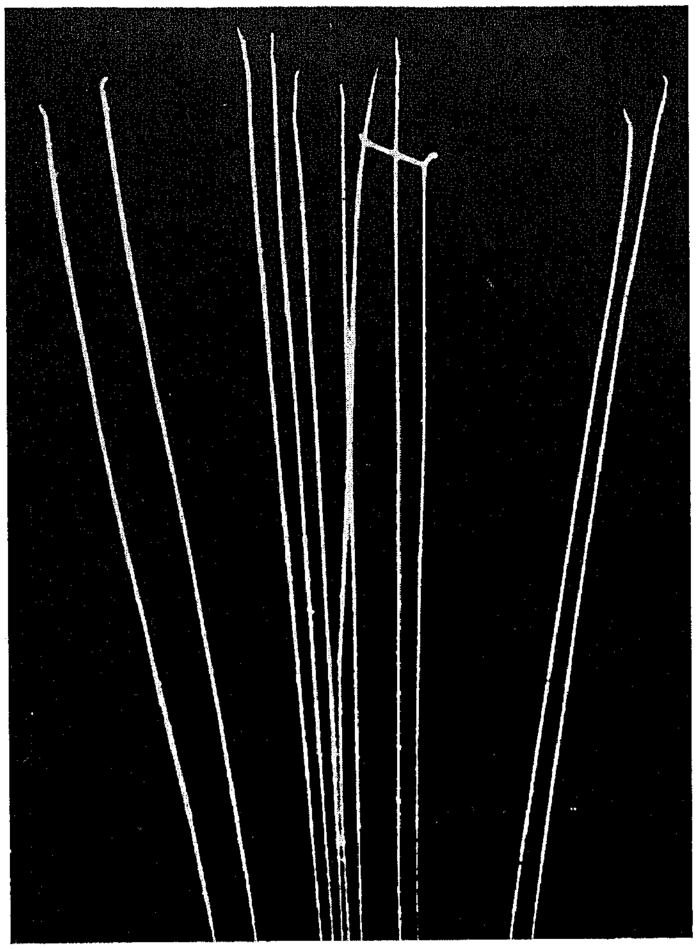

Fig. 1.—Tracks of α-particles in nitrogen. Some show small deflections resulting from nuclear encounters. The forked track shows a large deflection which is clearly the result of a single collision; the short arm of the fork is the track of the recoiling nucleus of nitrogen.

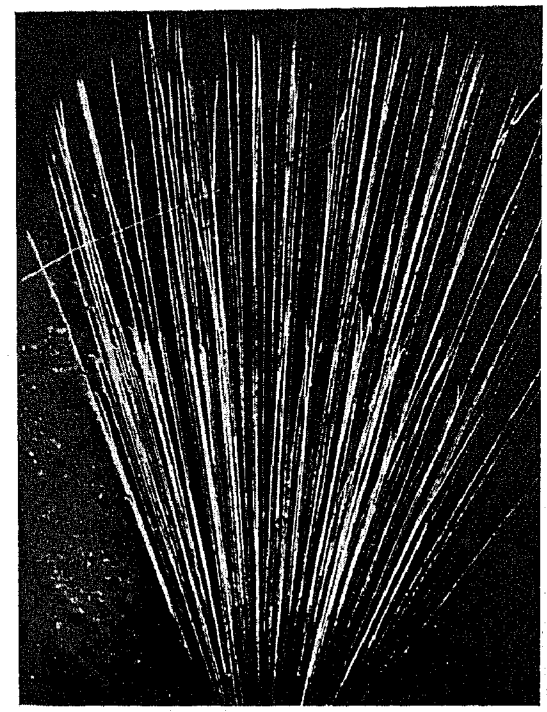

Fig. 2.—Photograph of tracks of α-particles, showing at the point indicated the ejection of a proton when a nitrogen nucleus is disintegrated by the capture of an α-particle. The long backward track is the track of the proton, the short track that of the oxygen nucleus formed as the result of the process:—

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{1}_{1}H + ^{17}_{8}O$$

Fig. 3.—Neutrons passing through nitrogen. A neutron has collided with a nitrogen nucleus, imparting such a velocity that the nitrogen nucleus produces a visible track. The neutrons give no other sign of their passage.

Plate 2

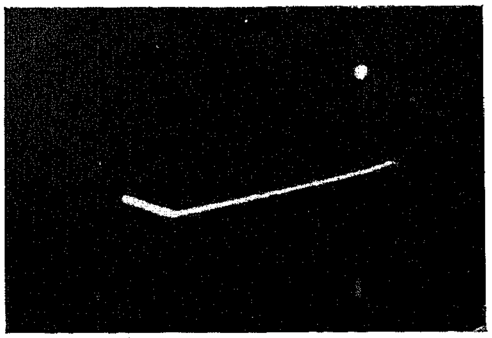

Fig. 4.—Neutrons passing through nitrogen. In this case a neutron has caused a disintegration of a nitrogen nucleus, ejecting an α-particle (the long arm) and leaving a boron nucleus (the short arm):—

$${}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{11}_{5}B + {}^{4}_{2}He$$

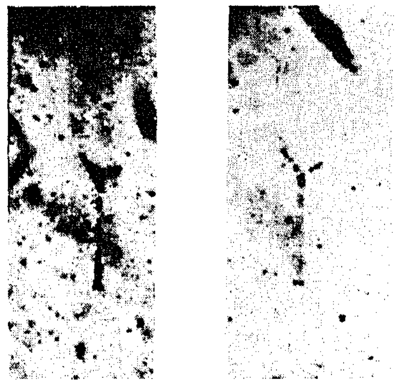

Fig. 5.—Two views of tracks in a photographic emulsion containing boron. A boron nucleus has captured a slow neutron and broken up into three parts according to the reaction:—

$${}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + {}^{3}_{1}H$$

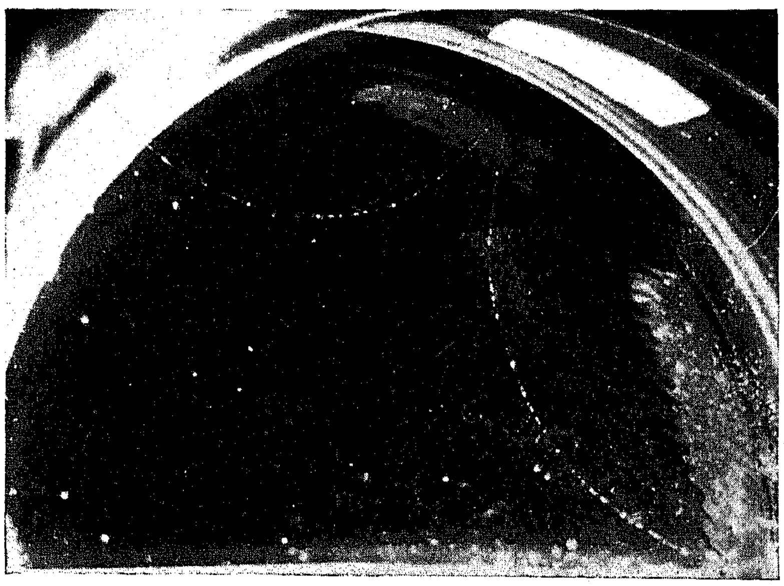

Fig. 6.—Photograph showing the creation of a pair of electrons, one negative (the upper track) and one positive, by a quantum of radiation. The difference of sign of charge is shown by the opposite curvatures in the magnetic field at right angles to the plane of the photograph. The reaction may be represented thus:—

$h\nu \rightarrow$ negative electron + positive electron + kinetic energy

the quantum units of $h/(2\pi)$. Now a nucleus which is built up from protons and electrons must have characteristics given by the vector sum of the characteristics of the individual particles; this must apply to the spins as rigidly as to the charges. Thus the carbon nucleus, containing 12 protons and 6 electrons, must have a spin of 0, 1, or 2 . . . according to the arrangement of the particles. The spin actually found from experiment is 0. The nitrogen nucleus, containing 14 protons and 7 electrons, should have a spin of $\frac{1}{2}$, $1\frac{1}{2}$, or $2\frac{1}{2}$, . . . etc., according to the particular arrangement. But the experimental value is 1. This was a very serious difficulty. It was not the only one, for other arguments also suggested that the electron could not be a general unit in the structure of the nucleus. This difficulty was removed a few years ago by the discovery of a new particle, the neutron.

The idea that there might exist particles with no electric charge had been put forward on various occasions, but the first suggestion of a neutral particle with the general properties of the neutron was made by Rutherford in 1920. He suggested that a proton and an electron might unite in a much closer way than they do in the hydrogen atom, so forming a particle with no net charge and with a mass nearly the same as that of the hydrogen atom. His view was that with such a particle as the first step in the formation of atomic nuclei from the two elementary units, the proton and the electron, it would be much easier to picture how heavy complex nuclei can be gradually built up from the simpler ones.

For some time no evidence for the existence of neutral particles was forthcoming. Then, in experiments on artificial transmutation similar to those I have previously mentioned, it was found that when beryllium is bombarded by α-particles a radiation is emitted which has the property of setting in motion atoms of the matter in its path. This property immediately suggests that the radiation must consist of particles. Investigation of the collisions of these particles with atoms of different masses showed that the mass of the new particle was about the same as that of the proton. Experiment also showed that these particles can pass easily through large thicknesses of matter, such as 10–20 cm. of lead. A proton of the same velocity as the new particle would be stopped by a thickness of 0·25 mm. of lead. Since the penetrating power of particles of the same mass and speed depends only on the charge carried by the particle, it was obvious that the new particle must have a very much smaller charge than the proton, i.e. none at all. Thus we have a new particle, the neutron, with no charge and a mass very nearly the same as that of the proton.

The neutron has only a transient existence in the free state. It is produced in a free state when an atomic nucleus is transformed in some way, e.g. by the bombardment of α-particles, as in the case of beryllium; in many cases by the bombardment of deuterons; and in a few cases by the photo-electric effect of a quantum radiation. The liberated neutron, owing to its lack of charge, passes freely through the structure of atoms in its path. It may collide with the nuclei and set them in motion (cf. Fig. 3), but finally it enters a nucleus and becomes incorporated into its structure, often causing a transmutation of the nucleus in the process (cf. Figs. 4 and 5, Plate 2). Its ultimate fate is to be bound with other neutrons and with protons in the structure of a nucleus.

Shortly after the appearance of the neutron another elementary particle was discovered, the positive counterpart of the electron. Evidence for the positive electron was obtained first by Anderson, and later by Blackett and Occhialini, in their investigations of the cosmic radiation. It was then found that positive electrons were created in the passage of electromagnetic radiation of high energy through matter. In the strong electric field near an atomic nucleus a high-energy quantum may disappear with the creation of a pair of electrons, one the ordinary negative electron and the other a particle of the same mass and spin but carrying a unit positive charge (see Fig. 6). The positive electrons have a very short life. While they exist they behave, except for their charge, in a similar way to the negative electrons, but sooner or later they have a very close encounter with a negative electron, and the two particles coalesce and disappear. The energy of the particles, both kinetic and in the form of mass, appears as radiation. Usually the positive electron will be moving slowly at the moment of annihilation and the total energy of the particles will correspond to the sum of their mass energies, i.e. 1 million volts, while their total momentum is zero. Thus to conserve momentum and energy two quanta, each of 500 000 volts, must be emitted in opposite directions.

Positive electrons are also emitted from the nuclei of certain unstable elements. It was discovered by M. and Mme. Curie-Joliot that the bombardment of some elements by α-particles resulted in the formation of bodies which showed the phenomenon of radioactivity. For example, when boron was bombarded by α-particles a product was formed which had the chemical properties of nitrogen but which emitted positive electrons and decayed with a definite half-value period. The scheme of transformation is represented thus:—

$$^{10}_{5}\mathrm{B} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{13}_{7}\mathrm{N} + \text{neutron}$$
$$^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + \text{positron}$$

Such artificial radioactive elements can now be produced in a variety of ways. Some decay with the emission of positive electrons and some with the emission of negative electrons; all with a characteristic period. (An example of the emission of a negative electron is the following:—

$$^{27}_{13}\mathrm{Al} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{28}_{13}\mathrm{Al} \rightarrow {}^{28}_{14}\mathrm{Si} + \text{negative electron}$$

A neutron is captured by an aluminium nucleus, forming an unstable nucleus which changes, with the emission of a negative electron, into a stable silicon nucleus.)

I return to the question of the structure of atomic nuclei. We have now four elementary particles to take part in the formation of matter—the negative and positive electrons, the proton, and the neutron. I have pointed out the argument from nuclear spins which speaks against the existence of negative electrons inside the nucleus. The same argument applies to the presence of positive electrons also. Other arguments lead to the same conclusion; for example, it seems impossible to provide a mechanism which would prevent an electron

from escaping immediately. Protons alone are not sufficient, but we can satisfy the requirements of mass and charge by using neutrons as well. A nucleus of atomic number Z and mass number A then contains Z protons and $(A-Z)$ neutrons. We assume* that the forces between the particles are of three types. The force between two protons is the usual Coulomb repelling force, the force between two neutrons is probably small, and the force between a neutron and a proton is assumed to be of the exchange type, i.e. similar to that between a hydrogen atom and a hydrogen ion, a strong attraction at large distances changing to a repulsion at very small distances. In a stable nucleus there must be a balance between the repelling forces between the protons and the attracting forces between neutron and proton. The neutron-proton force tends to make the number of neutrons and protons in the nucleus equal and there are several light elements, among them the most stable, for which this relation holds, e.g. ${}^{2}_{1}H$, ${}^{4}_{2}He$, ${}^{6}_{3}Li$, ${}^{10}_{5}B$, ${}^{12}_{6}C$, ${}^{14}_{7}N$, ${}^{16}_{8}O$, etc. The Coulomb forces between the protons tend to keep the number of protons less than the number of neutrons. This tendency increases with the number of protons present and accounts for the fact that in heavy elements the nuclei contain appreciably more neutrons than protons. Thus the gold nucleus, of mass 197 and number 79, contains 118 neutrons and 79 protons. Generally, there are more neutrons in matter than there are protons.

We must consider now the unstable nuclei, those nuclei which break up spontaneously with the emission of a particle. The emission of a heavy particle, namely a proton, an α-particle, or a neutron, is relatively easy to explain. But some nuclei break up with the emission of electrons, in spite of our arguments and our belief that there are no electrons in an atomic nucleus. We are forced to suppose that these electrons are formed at the very moment of emission. More precisely, if the nucleus is unstable because it contains too many neutrons, we assume that one of the neutrons may transform into a proton and a negative electron, the electron being immediately emitted. If the nucleus has too many protons, the proton is supposed to transform into a neutron and a positive electron (compare the instability of ${}^{28}_{13}Al$ and ${}^{13}_{7}N$ described above). Thus

Neutron $\rightarrow$ proton + negative electron

and

Proton $\rightarrow$ neutron + positive electron

Now while these equations satisfy the requirement of conservation of charge they do not satisfy that of the conservation of spin; for the neutron, the proton, and the electron each have a spin of $\frac{1}{2}$. This difficulty can be avoided by introducing a new particle which has no charge, a very small mass (electron mass or less), and a spin of $\frac{1}{2}$. We then write†

Neutron $\rightarrow$ proton + negative electron + neutrino
Proton $\rightarrow$ neutron + positive eleutron + neutrino

* The arguments used here are rather loose, but they bring out the point in a simple way.

† This relation does not mean that the neutron is composed of proton, negative electron, and neutrino, but that it is able to transform into these three particles: similarly for the proton.

where this new hypothetical particle is called a "neutrino."

The neutrino was first introduced by Pauli in order to retain conservation of energy in the β-ray transformations. There is no direct evidence for the existence of this particle and, in view of its properties, direct evidence will be difficult to obtain; but it seems impossible without it either to conserve energy or to conserve spin in the β-ray transformations.

I conclude with a brief summary of the present position. We know that all matter is composed of atoms, and that the atom consists of negative electrons and a nucleus. We assume that the nuclei are built up from protons and neutrons, and thus all matter is finally composed of these three particles—the negative electron, the proton, and the neutron. In transient phenomena a fourth particle, the positive electron, appears; and perhaps also a fifth, the neutrino.

The quantum mechanics gives a satisfactory account of the behaviour of atomic electrons; and hence all chemistry, macroscopic phenomena, and nearly all atomic phenomena, can be explained. The picture is not so satisfactory when we consider nuclear phenomena. The quantum mechanics might possibly be sufficient to describe the behaviour of protons and neutrons in a nucleus if we knew the forces which control them. On plausible assumptions about these forces we can give an explanation of some of the general relations between atomic nuclei, but we have no complete theory even for the stable nuclei. To explain the behaviour of unstable nuclei we have to suppose that, under certain conditions within the nucleus, neutron and proton can transform one into the other, and then in addition we have to invoke the aid of another particle, the neutrino, or we are forced to abandon the established laws of conservation of energy and spin. This account of β-ray transformation is thus at present little more than a description and not an explanation in terms of known phenomena.

We must then ask: What is the nature of this connection between neutron and proton? Are they perhaps different states of the same elementary particle? Which are the real elementary particles—electrons negative and positive, protons, or neutrons? Must we add the neutrino? Why are there particles of two kinds, namely, electrons with small mass, and proton and neutron with large mass? Should we also bring in the photon or quantum of radiation? That there is some connection between particles and the electromagnetic field is shown by the fact that electrons can be annihilated and converted into electromagnetic radiation and that, conversely, radiation can create electrons. It may be, as Born suggests, that we must return to the old view in which the electromagnetic field is the carrier of all physical processes and that the particles are in a sense singularities of this field.

While most of the problems of Kelvin's time no longer trouble us, and we know a great deal more about "the relation between ether, electricity, and ponderable matter," the solution itself of these problems has brought with it new questions which seem even more perplexing than the old.

FUNDAMENTAL ELECTRICAL MEASUREMENTS*

By SIR FRANK E. SMITH, K.C.B., C.B.E., D.Sc., F.R.S.

(*Lecture delivered before the* METER AND INSTRUMENT SECTION, *7th May*, 1937.)

The subject on which I have been asked to address you cannot be called a very popular one. In textbooks of electricity it is not uncommon to find the portions dealing with fundamental measurements in small type, with a recommendation to omit them on a first reading. This recommendation is usually followed, and very often the second reading is similarly curtailed. This, I think, is unfortunate, for the subject is not really difficult for teaching purposes, the experimental side being simple. For many years I made a profound study of the subject, and the more I studied it the more did I admire the genius and clear vision of those who planned such measurements exactly three-quarters of a century ago. I refer to Weber, Kelvin, Maxwell, Jenkin, Rayleigh, and a few others who laid the foundations of electrical measurement securely and well. Indeed, it is because of the work of these men that electricity has become the science of exact measurement, and I have no doubt that it is this exact measurement that has led to the rapid development of electrical engineering.

This evening I propose to deal with the subject of fundamental measurements in what is perhaps a novel manner. The historical method was adopted by Sir Richard Glazebrook in a Kelvin Lecture exactly 25 years ago, but to-night I propose to deal with the subject in three sections. In the first I shall consider the type of fundamental measurements we might adopt if we started *de novo* but with our present knowledge.

I shall not deal with the subject mathematically, but I shall give you in passing a glimpse of the electron as the unit quantity of electricity; I shall attempt to give you some conception of current and of resistance, and in the light of our present-day knowledge I shall ask you to consider whether a good fundamental system of measurements could be based on such knowledge. I shall conclude the first part of this lecture by admitting the possibility of such a system. I shall, however, deem it to be unnecessary and possibly undesirable.

In the second part I shall make measurements of electric quantity, current, and resistance, in terms of the centimetre, gramme, and second. I shall attempt to show you that Kelvin, Maxwell, Weber, and others, in devising a system of fundamental measurements, did not devise anything complex, but something really simple. The difficulty is not, as is often supposed, in realizing the fundamental units of electricity, but in realizing them with great precision. The conception of the units is not difficult, and, if one is content with moderate precision of measurement, electric quantity (in electrostatic and in electromagnetic measure), electric current, and even resistance can be measured in terms of the centimetre, gramme, and second, with apparatus costing but a few shillings, as I hope to show you to-night.

Finally, in the third section I shall try to give you a fleeting picture of the state of precise electrical measurements to-day. Such measurements are the basis of all electric meters.

As a curtain-raiser, I ask you for a moment to consider the state of electrical engineering in the middle of last century, when fundamental measurements were first planned.

1. In 1860 electrical engineering was practically confined to telegraphy, and this Institution of Electrical Engineers did not exist. The transmission of signals by means of electric currents was suggested by Ampère in 1821, and shortly afterwards Gauss and Weber constructed a telegraph line over a distance of nearly 2 miles. In 1831 Henry produced in America a successful system for transmitting signals, but it was left to Morse, in 1844, to establish the first long-distance line from Baltimore to Washington. In 1857 the first Atlantic cable was laid. It is true that in 1860 there were dynamos—they were, however, very small machines and it was not until 1866 that electromagnets were used in dynamo machines. In 1860 resistances were expressed in terms of a length of telegraph wire or a length of some other wire, and voltages were given in terms of the number of batteries used—usually the Daniell cell was taken as a standard. There were no ammeters, the only current-measuring devices being galvanometers. More usually the current was guessed and not measured.

In these circumstances, inasmuch as electrical engineering as a source of power, of light, and of heat, did not exist, it seems at first sight surprising that Kelvin, Maxwell, Rayleigh, and others, should have taken such great pains to devise a novel and most precise system of electrical measurements. These men had remarkable vision and, even if they did not foresee the electrical engineering of to-day, they did at least believe that electricity was the most likely agent to solve the big engineering problem of their day.

What, you may ask, was the big engineering problem? Seventy-five years ago the great difficulty was the transmission of power over long distances. At the coal mines there were long link motions known as "flat rods," which transmitted power from a steam engine to the pit mouth. On the Continent power was transmitted for a mile or more by rapidly-moving ropes carried on overhead pulleys. Compressed air was used to drive tramcars for short distances, but there was no system of power transmission operating over many miles. With the advent of the gas engine, proposals to transmit power by means of coal gas were strongly supported.

* The lecture was an experimental one, the intention being to demonstrate the ease with which electric quantity, current, and resistance, could be measured with simple and cheap apparatus. Obviously this main objective could be attained with the audience only, but it is hoped that the reader will appreciate the simplicity of the measurements made.

As a possible solution of the problem, electricity gained increasing attention. Electrical power could be transmitted through wires to produce power, heat, and light. The dynamo—small and inefficient though it was—was in existence, and the steam engine had long since been invented. Could it be that Kelvin and the others associated with him were convinced that the power transmission systems of the future would be electrical, and that they had visions of some aspects of modern electrical engineering? I do not know. This, however, is certain—that they devised a system of measurements unparalleled in any other branch of engineering and one which has not yet been superseded.

The knowledge of the nature of electricity was in those days very meagre. It was thought of as a state similar to the transmission of heat through a wire or the propagation of sound through a tube, but no one knew what it was. True, we do not know to-day what it is, but we do know of the existence of electrons, protons, neutrons, etc., the properties of which Professor Chadwick told us in his Kelvin Lecture two weeks ago.

Let me turn for a moment to a picture of modern knowledge, but not a detailed one, lest the trees obscure our view of the forest. All that I desire to put before you is some mental picture of what an electric quantity is, what an electric current is, and what an electric resistance is. Our present system of fundamental measurements is seventy-five years old, and it may be leading us astray: let us see.

Thanks to the work of J. J. Thomson, Rutherford, and others, we know to-day that all matter consists of electric charges. An atom is made up of negatively charged particles called electrons rotating round a central, positively charged nucleus. The other particles called neutrons, positrons, etc., we will not talk about to-night, for, as Professor Chadwick reminded us, they play no important part in ordinary conductors of electricity like copper.

It appears certain that the smallest quantity of electricity that can exist is the electron, and that Nature's unit of electric quantity is the electron and not the coulomb, which is the unit quantity in electrical engineering. The size of the electron is known, as also is its mass. Thus 1 gramme of hydrogen contains approximately $0 \cdot 6 \times 10^{24}$ atoms, and, as each atom contains one electron, there are $0 \cdot 6 \times 10^{24}$ electrons in 1 gramme of hydrogen. The mass of the electron is about $9 \cdot 0 \times 10^{-28}$ gramme, and the proton weighs about $1 \cdot 66 \times 10^{-24}$ gramme. The question is, can we utilize this knowledge and measure all electrical quantities in terms of the electron? We shall see presently that we can, though it may not be advantageous to do so.

But before considering how to measure electric quantities in terms of electrons, let us consider what we mean by conductivity or resistance, and why it is that a conductor like copper increases in resistance with rise of temperature and at exceedingly low temperatures has little or no resistance.

An atom of copper consists of a nucleus having an excess of 29 unit positive charges, and around this nucleus 29 electrons, i.e. unit negative charges, move in paths somewhat similar to the orbital movements of the planets around the sun. Roughly speaking, there are four orbital systems containing 2, 8, 18, and 1, electrons respectively.

It must be remembered that the atom itself is a very open structure, and when we speak of the size of an atom we mean a sphere having a radius extending from the nucleus to a distance exceeding the farthermost electron. The size of the nucleus compared with the size of the atom is about that of a small shot compared with the size of this room. Most of the atom is empty space.

The atoms of the metals always have one or more electrons which are lightly held. These "loose" electrons always belong to the outermost rings, and are more or less free to move about in the structure. We see at once why metals are conductors of electricity; it is because many of the electrons can move about so easily. When a current of electricity flows along a metal wire, it is the electrons that constitute the flowing stream. In their motion the electrons collide with atoms, and this impediment to their motion constitutes "resistance."

When a metal is heated, the electrons move more quickly to and fro and may break away into the open. Electrons are easily pulled out of a hot wire, as in the filament of a wireless valve.

At this point it is necessary to say something about the meaning of temperature. The atoms of all substances are normally in a state of rapid vibration. The greater this rate of vibration is, the higher is the temperature; the lower the rate of vibration, the lower the temperature, and when the vibration is zero the temperature also is zero. This latter is called the absolute zero of temperature.

As already stated, some of the electrons in a metal are free to wander about, and when an appropriate force is applied to them, as by a moving magnetic field, the electrons travel at right angles to the field and at right angles to the direction of motion of the field. If this force makes them move transversely to the wire they collide with the atoms, and the atoms, and therefore the wire, move. If the electrons move along the wire, an electric current flows, but the electrons still strike the vibrating atoms and the impact causes the atoms to vibrate still more—that is, the temperature rises. In some cases, as with lead at very low temperatures, the atoms vibrate very slowly and the electrons can travel considerable distances without hitting the atoms, and, since there is practically no resistance to the flow, a current once started might continue almost indefinitely.

Of course this is only a very rough picture I have drawn; not only do many details require to be filled in, but many important features have not even been mentioned.

The conception is, however, very useful. If we hammer a piece of copper, the distribution and arrangement of the crystals is altered, and the electrons find the new arrangement offers more resistance to their passage. So hard copper has a greater resistivity than annealed copper.

Again if, say, copper and zinc are joined together, some of the free or loosely attached electrons of the one metal travel into the other—the number depends on the temperature—and if there be a circuit of two such junctions, one at a high temperature and the other at a

low, there cannot be a state of equilibrium, and a current will flow. Such junctions are called thermojunctions.

Again, let a rod of copper be partly immersed in a solution, say, of common salt. Many of the "odd" electrons leave the copper and enter the solution, leaving the copper with an excess positive charge. If, instead of copper, we use zinc, the action is less marked. So copper is electro-positive compared with zinc, and a voltaic battery may thus be formed with copper and zinc in a solution of common salt.

In dilute solutions of metallic salts research has carried us farther. Thus in a very dilute solution of copper chloride the copper and the chlorine particles separate. Each copper atom loses one electron and the chlorine atoms gain correspondingly. The copper atoms are now called kations and the chlorine atoms anions. If a current passes through such a solution, every electron that passes will restore one atom of copper to an equilibrium state and deposit it in solid form.

The mass of a copper atom is about $1\cdot05 \times 10^{-22}$ gramme, so to deposit 1 gramme of copper requires

$$\frac{1}{1\cdot05 \times 10^{-22}} = 0\cdot95 \times 10^{22} \text{ electrons.}$$

Electrolysis thus affords a means of measuring the number of electrons passing in a circuit.

It is well known that 1 518 coulombs of electricity are required to deposit 1 gramme of copper. Hence the number of electrons in 1 coulomb is

$$\frac{0\cdot95 \times 10^{22}}{1\,518} = 6\cdot2 \times 10^{18}$$

This is a practical way of measuring an electric quantity in electrons. However, to obtain great accuracy, the mass of the atom is required to be known with precision.

Can we, in some comparable manner, measure an electrical pressure or voltage? A difference of voltage means that there are more electrons in one unit volume than in another, the conditions being otherwise the same. Since we can measure the number of electrons passing in a circuit, we might, by suitable means, pass a known number of electrons into a sphere, say of 1 cm. radius, and call the unit of voltage that difference of pressure produced by the addition of one electron.

To measure the quantity it might be necessary to charge and discharge the sphere thousands of times by a make-and-break contact, but the measurement would present no real difficulty. It is clear, therefore, that quantity in terms of the electron, current in terms of the electron, and voltage in terms of the electron, can all be measured, and with refined apparatus considerable precision could be obtained. But a system of this kind was not the system of those pioneers of 1862 nor is it the system of to-day. Let us see if the 1862 system is not, after all, simpler in practice.

2. In 1862 there were defined four main quantities, and on these four definitions practically all electrical measurements are based.

An electric quantity was defined in two ways, one definition being based on electricity when it is stationary and the other when it is in motion. The definitions are given by the two well-known equations

$$F = \frac{ee_1}{d^2}$$

$$\text{and} \quad F = \frac{2\pi im}{r}$$

In the first equation the two stationary charges e and e_1 are d centimetres apart and the force between them is F dynes. In the second the current i passes through a circle of radius r with a magnetic pole m at the centre. The force on m is F dynes. The current i is of course the quantity of electricity passing per second.

The latter definition involves a magnetic pole, and this was defined in a similar way to the electrostatic unit of quantity, namely:—

$$F = \frac{mm_1}{d^2}$$

Finally, the work done when a current i flows through a resistance was defined as

$$W = i^2Rt$$

R being the resistance, t the time, and W the work done in ergs.

All the measurements in electrical engineering depend primarily on these four equations. Whether the measurement be one of current, power, heat losses, or flux density, the measurements are based on these definitions. They ignore the true nature of electricity; they ignore the true nature of resistance and voltage. The system of measurements is based on a mechanical system, on a length—the centimetre, a mass—the gramme, and a time—the second.

I propose now to measure a quantity of electricity based on the first equation.

Here I have a large sphere 15 cm. in diameter; it is connected to two small spheres each 1 cm. in diameter, the one being fixed and the other movable (see Fig. 1, Plate 1, facing page 706). The weight of the small movable sphere is $0\cdot040$ gramme and the length of the suspension is 50 cm.

I proceed to charge the large sphere and with it, of course, the small ones. The charge on the large sphere will be 15 times as great as that on either of the small spheres, because its capacity is 15 times as great. The charge on the small spheres will be the same. I measure the deflection, and for convenience a magnified deflection is shown by the shadows. The distance is 6 cm. Then

$$F = \frac{e^2}{6^2}$$

and the force F due to gravity on the mass of $0\cdot040$ gramme which balances the repulsion is

$$F = 0\cdot040 \times 981 \times \frac{6}{50}$$
$$= 4\cdot7 \text{ approx.}$$

So $$e^2 = 4\cdot7 \times 36 = 169\cdot2$$

$$\therefore \quad e = 13 \text{ approx.}$$

So the charge on the big sphere $= 15 \times 13 = 195$ electrostatic units.

It is of interest to compare this quantity with the coulomb used by electrical engineers to-day, remembering that the passage of one coulomb per second is 1 ampere. I make the comparison by discharging the sphere through a ballistic galvanometer. The deflection obtained is 110 divisions.

Next I pass 1/10th of a microampere through the same ballistic galvanometer for exactly 1 second, that is, I pass one ten-millionth of a coulomb. This gives a deflection of 160 divisions. So the coulomb is bigger than the electrostatic unit in the proportion

$$\frac{195 \times 10^7 \times 160}{1 \times 110} = 2 \cdot 84 \times 10^9$$

Presently we shall see what this ratio means.

I now proceed to measure a current in electromagnetic measure, that is, a current based on the definition

$$F = \frac{2\pi nim}{r}$$

where n is the number of turns in the coil. To determine m I measure the strength of a magnetic pole by the formula

$$F = \frac{mm_1}{d^2}$$

Here are two magnets similar in all respects, and by using one as the arm of a small balance I measure the product of the strengths of the poles (see Fig. 2, Plate 1).

The balancing weight is $0 \cdot 029$ gramme and the balancing force is therefore 29 dynes. d is 5 cm. Substituting these values in the formula we have $29 = m^2/5^2$, therefore $m^2 = 725$ and $m = 27$ approximately, m being in c.g.s. units.

Associated with the magnetic balance is a small coil with vertical axis, one of the poles of the suspended magnet being for practical purposes at the centre of the coil.

A current is passed through the coil till the force is the same as before, that is, 29 dynes.

$$\text{Hence } 29 = \frac{2\pi ni27}{r}$$

Now $n = 5$ and $r = 3 \cdot 14$. Substituting these values we find that $i = 0 \cdot 10$ approx., this current being in electromagnetic measure. But the ammeter in the circuit registers exactly 1 ampere. So our c.g.s. unit of current is 10 times as big as the ampere, and our electromagnetic unit of quantity is not 1 coulomb but is equal to 10 coulombs.

The ratio of the two units of electricity defined in 1862 is, according to the measurements made here to-day, $2 \cdot 84 \times 10^{10}$, which is accurate within about 4 per cent. This ratio is the velocity of light in centimetres per second. As you all know, light is an electromagnetic phenomenon, and the ratio of the two units of quantity as defined in 1862 is its velocity.

Perhaps you will allow me for a moment to show you that, as defined (and you will observe that the permeability and inductive capacity of the medium have been taken as unity and of no dimensions), the ratio of the two units is a velocity.

All forces are measured as the product of a mass into an acceleration, and an acceleration is the change of velocity with time.

Hence the dimensional equations:—

$$\text{Force} = \left[\frac{ML}{TT}\right] = \left[\frac{ML}{T^2}\right]$$

$$\text{also} \quad \text{Force} = \left[\frac{e^2}{L^2}\right] = \left[\frac{m^2}{L^2}\right]$$

$$\text{also} \quad \text{Force} = \left[\frac{e_m m}{TL}\right]$$

where e_m is the electromagnetic unit of quantity.

From which it follows that

$$\left[\frac{e^2m^2}{L^2L^2}\right] = \left[\frac{e_m^2 m^2}{T^2L^2}\right]$$

$$\text{Hence} \quad \left[\frac{e^2}{e_m^2}\right] = \left[\frac{L^2}{T^2}\right] \quad \text{and} \quad \left[\frac{e}{e_m}\right] = \left[\frac{L}{T}\right]$$

that is, the ratio e/e_m has the dimensions of a velocity.

Many of you will, I know, object to the omission of κ and μ from the equations, κ being the dielectric constant of vacuous space and μ the corresponding magnetic permeability. If we write down equations which include κ and μ in the definitions of electromagnetic and electrostatic units of quantity, we get

$$\left[\frac{1}{\sqrt{(\kappa\mu)}}\right] = \left[\frac{L}{T}\right]$$

The separate dimensions of κ and of μ are not known. The equation tells us, however, that the ratio of the two units is equal to $1/\sqrt{(\kappa\mu)}$, and this has the dimensions of a velocity. To obtain some idea of this velocity, imagine a plane surface charged with electricity to the surface density σ and let it move in its own plane with a velocity v. Such a moving electrified sheet would be equivalent to a current sheet, the current passing through unit breadth of the sheet being σv in electrostatic measure and $\sigma v/\sqrt{(\kappa\mu)}$ in electromagnetic measure. If a similar and parallel current sheet with charge of density σ' moves in the same direction and with the same velocity the electrostatic repulsion per unit area between the two surfaces is $2\pi\sigma\sigma'$ and the electromagnetic attraction between the two current sheets is $2\pi\sigma\sigma' v^2\kappa\mu$. In light waves there is neither attraction nor repulsion, that is

$$2\pi\sigma\sigma' = 2\pi\sigma\sigma' v^2\kappa\mu$$

that is, the velocity for no attraction or repulsion is given by the relationship

$$v = \frac{1}{\sqrt{(\kappa\mu)}}$$

This velocity is about 3×10^{10} cm. per sec.

The next fundamental measurement I propose to make is that of resistance.

Here I have a large circular coil of 100 turns and 30 cm. radius (see Fig. 3, Plate 1). From the definition

of unit current we know that the intensity of the magnetic field at the centre of the coil when a current i passes through it is

$$\frac{2\pi ni}{r_1}$$

where n is the number of turns, r_1 the radius, and i the current. The value of $2\pi n/r_1$ is 21. I will call this value C. The intensity of the field at the centre of the coil is therefore Ci.

Coaxial and co-planar with this large coil is a much smaller coil of 3 000 turns and 5 cm. radius. The effective area of this coil is $\pi r_2^2 n_2$, the value of which is 236 000. I call this effective area A.

If a ballistic galvanometer is placed in series with this small coil, the quantity Q_1 of electricity passing through the circuit containing it when the current i through the larger one is made or broken is approximately

$$Q_1 = \frac{CAi_1}{R}$$

where R is the resistance of the circuit. (The assumption is made that the field is uniform over the cross-section of the smaller coil, but in the apparatus now considered the error is only about 1 per cent.)

If in a second experiment the circuit of the large coil includes the ballistic galvanometer and is made for t seconds only (where t is about 1 second), the quantity Q_2 of electricity passing through the galvanometer is

$$Q_2 = i_2 t$$

Combining the two equations we have

$$\frac{Q_1}{Q_2} = \frac{CAi_1}{Ri_2 t}$$

so that

$$R = \frac{Q_2}{Q_1} \cdot \frac{CAi_1}{ti_2}$$

In the apparatus before you it is necessary for i_1 to be large to get a reasonably large deflection, and for i_2 to be very small. By a simple shunt arrangement I have arranged the ratio i_1/i_2 to be exactly 5 000 000 to 1.

By observing deflections you observe that Q_2/Q_1 is $100/33 \cdot 5 = 3 \cdot 0$, and as t is exactly 1 second we have

$$\begin{aligned} R &= 3\cdot 0 \times 21 \times 236\,000 \times 5\,000\,000 \\ &= 75 \times 10^{12} \text{ c.g.s. units.} \end{aligned}$$

Since the ohm is defined as 10^9 c.g.s. units, the resistance of the small coil and galvanometer circuit is measured to be 75 000 ohms. This is known to be approximately correct.

3. Now I come to the last part of my address; one that lasts but a few minutes and in which I shall give a fleeting glimpse of the apparatus which is used to-day for fundamental measurements of precision.

You will observe that material standards consisted of iron, of mercury, and of copper. In this country a standard mile of a special copper wire was very much favoured, and I have here two such standards which were used in 1862. Incidentally the conducting power of the "pure" copper of those days varied by over 10 per cent.

In the years intervening between 1862 and the present day fundamental measurements have largely been confined to two quantities, current and resistance.

Current has almost invariably been measured by some form of current balance in which two coil systems are employed, one of them being fixed and the other movable. The movable coil takes the place of the magnet in our simple current balance here, the coil having an advantage over a magnet, inasmuch as it is only necessary to know its dimensions accurately to determine the intensity of the magnetic field due to unit current passing through it.

Lord Rayleigh was one of the first to make a fundamental measurement of current. He used a system of 3 coils, two being fixed and the third suspended midway between them, each being wound with ordinary silk-covered wire.

It was at the beginning of this century that Viriamu Jones pleaded for a new epoch in fundamental measurements. He urged that "instead of building current balances with string and glue let them be built with the finest engineering tools and let them be permanent, so that measurements can at any time be checked."

So it was that in 1908 the Ayrton–Jones current balance of the National Physical Laboratory was built (see Fig. 4, Plate 2). In this work Professor Mather and I took the leading parts and succeeded in measuring current in terms of the centimetre, gramme, and second, with an error of a few parts only in 100 000. The coils are of bare copper wire wound in special grooves in marble. Their dimensions can be checked at any time, and a measurement of current occupies only about 20 minutes. There is little doubt that this balance *did* mark a new epoch in fundamental measurements, for balances in other countries have been built also for permanency, and the agreement between the results gives great satisfaction to electrical engineers.

First let me give you some idea of the chaos which existed in 1862, when in all there were 13 standards of resistance in use. The following table gives 7 of these:—

Name.	Nature.
Jacobi.	25 ft. of copper wire weighing 25 grammes.
Siemens.	1 metre of mercury 1 mm.^{2} cross-section.
Digney.	1 000 metres of iron wire, 4 mm. diameter.
Matthiessen.	1 mile of pure annealed copper wire $\frac{1}{16}$ in. diameter.
Varley.	1 mile of a special copper wire $\frac{1}{16}$ in. diameter.
Wheatstone.	1 ft. of copper wire weighing 100 grains.
German mile.	8 238 yards of iron wire $\frac{1}{6}$ in. diameter.

Here are the results obtained by Great Britain and the United States.

International Ampere in terms of the Ampere (*C.G.S.*).

Country.	Method.	Value.
Great Britain.	Ayrton–Jones current balance.	0·99986
United States.	Rayleigh type of current balance.	0·99993

As with the current balance, so with the measurement of resistance. The measurement of resistance, however, is much more difficult than that of current.

It was in 1910 that the Lorenz apparatus of the N.P.L. was completed (see Fig. 5, Plate 2). Again all the coils were of bare copper wire, and precautions were taken to ensure that every measurement of length and of permeability could be checked at any time. The principle is that of a homopolar machine, and in practice measurements were made, and can be made to-day, with the greatest possible ease and accuracy. The great trouble which Ayrton and Callender experienced in their Lorenz apparatus was due to thermoelectric effects at the brushes, but the special wire brushes designed for the N.P.L. apparatus, together with the cooling arrangements, made the thermoelectric effects very small and untroublesome.

To-day there are four countries which have made precise measurements of resistance in the c.g.s. system, with the following results.

International Ohm in terms of the Ohm (*C.G.S.*).

Country.	Method.	Value.
Great Britain.	Lorenz (Smith);	1·00050
	Campbell.	1·00050
Germany.	Self-inductance.	1·00059
Japan.	Mutual inductance.	1·00046
United States.	Self-inductance.	1·00045

And what of to-day? I am very glad to say, and I think you electrical engineers may well be proud of the fact, that this country took the lead in fundamental electrical measurements in 1862 and we have led ever since. No other country in the world has finer equipment than we have, and no other country has contributed more to the theory of the subject.

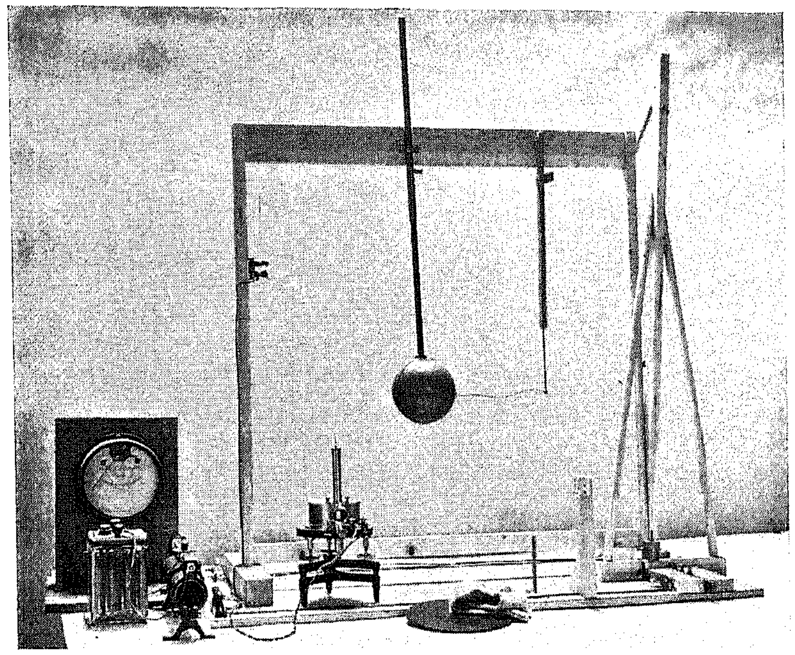

Fig. 1.—Apparatus used for measurement of electric quantity in absolute measure.

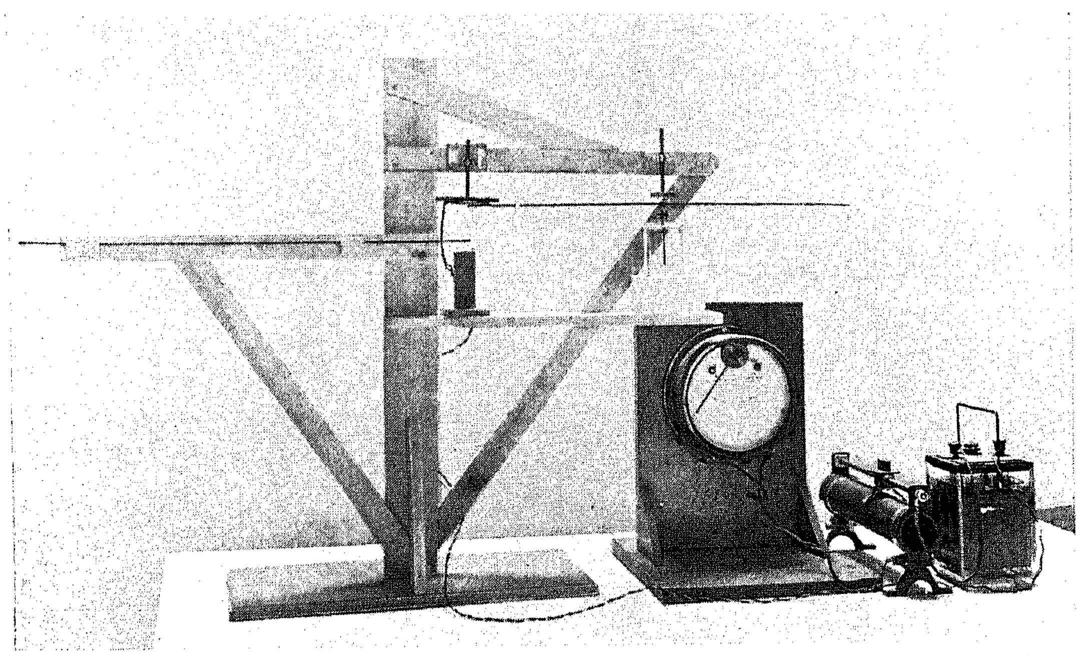

Fig. 2.—Simple apparatus used for measurement of magnetic pole strength in absolute measure and for measurement of current in absolute measure.

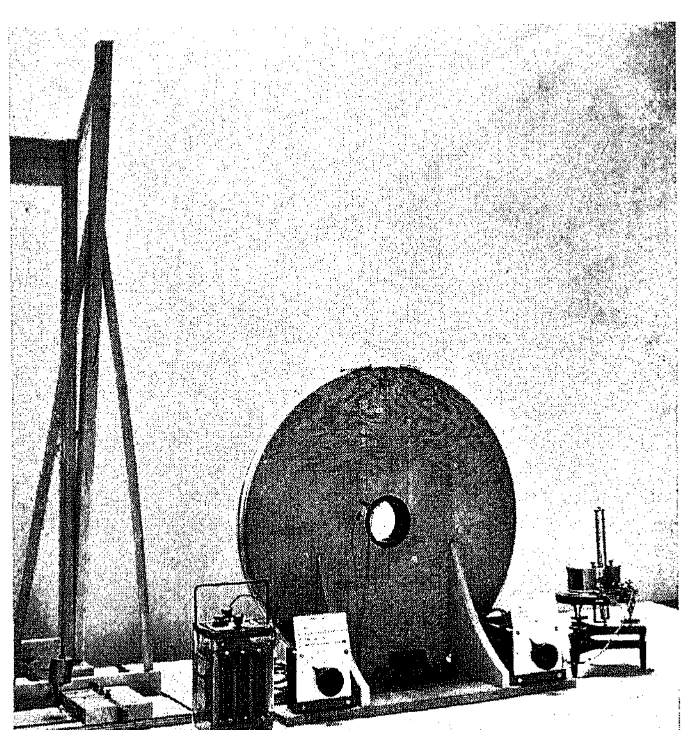

Fig. 3.—Apparatus used for measurement of electric resistance in absolute measure.

(*Facing page* 706.)

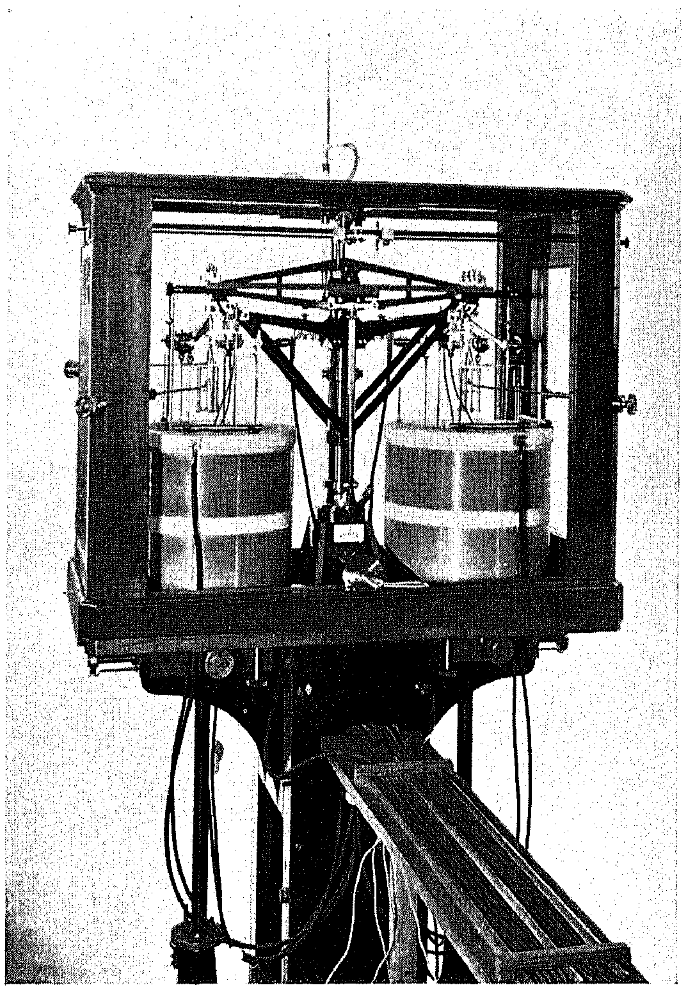

Fig. 4.—Current balance.

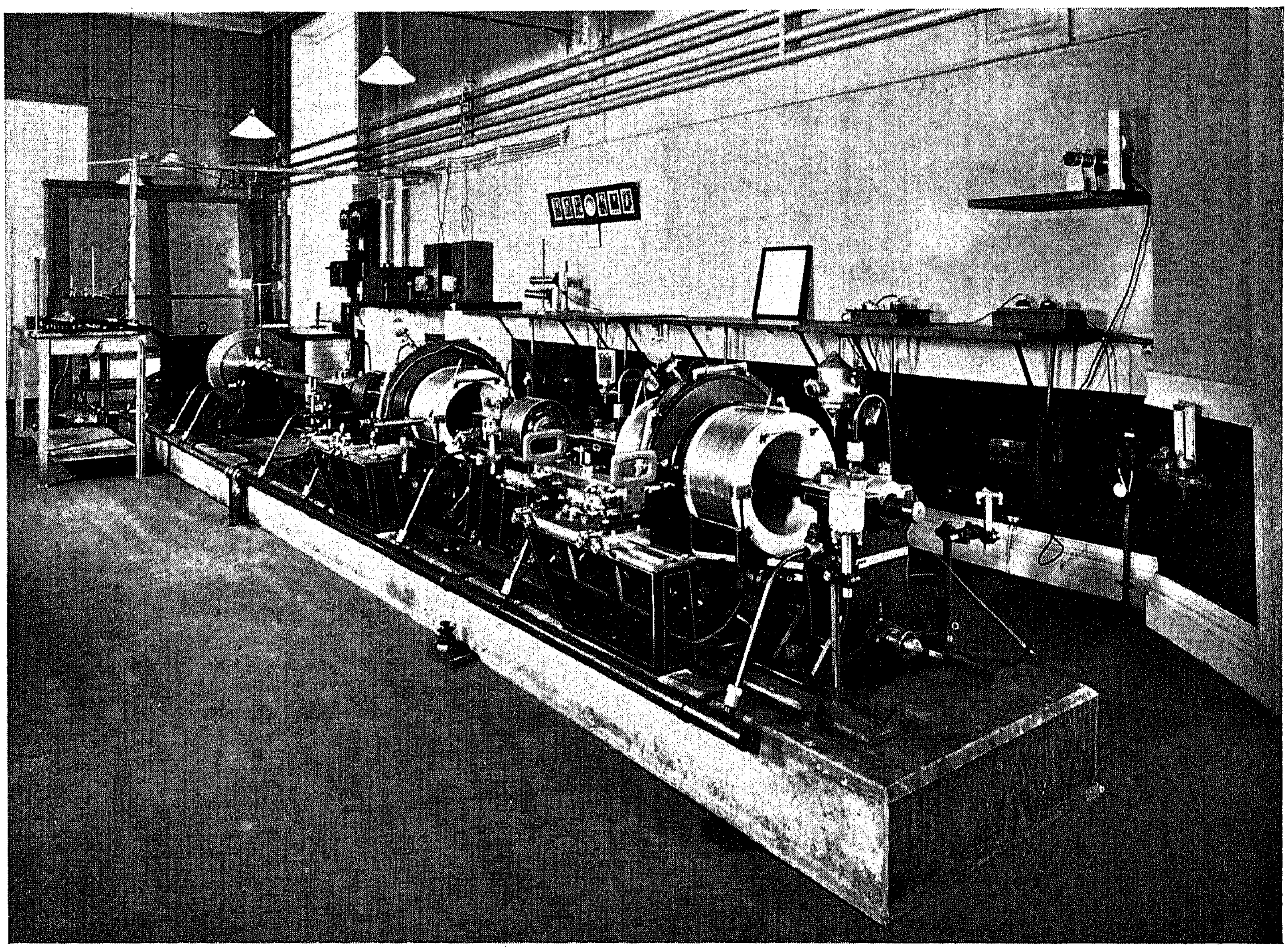

Fig. 5.—Lorenz apparatus.

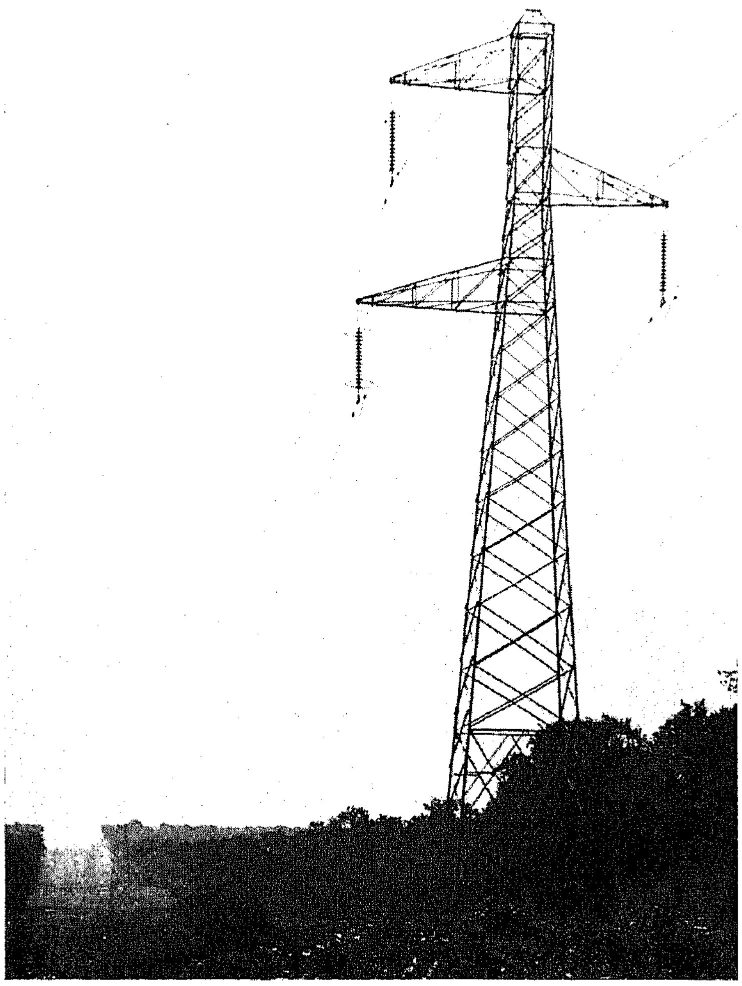

Fig. 3.—Type of tower used on 220-kV lines.

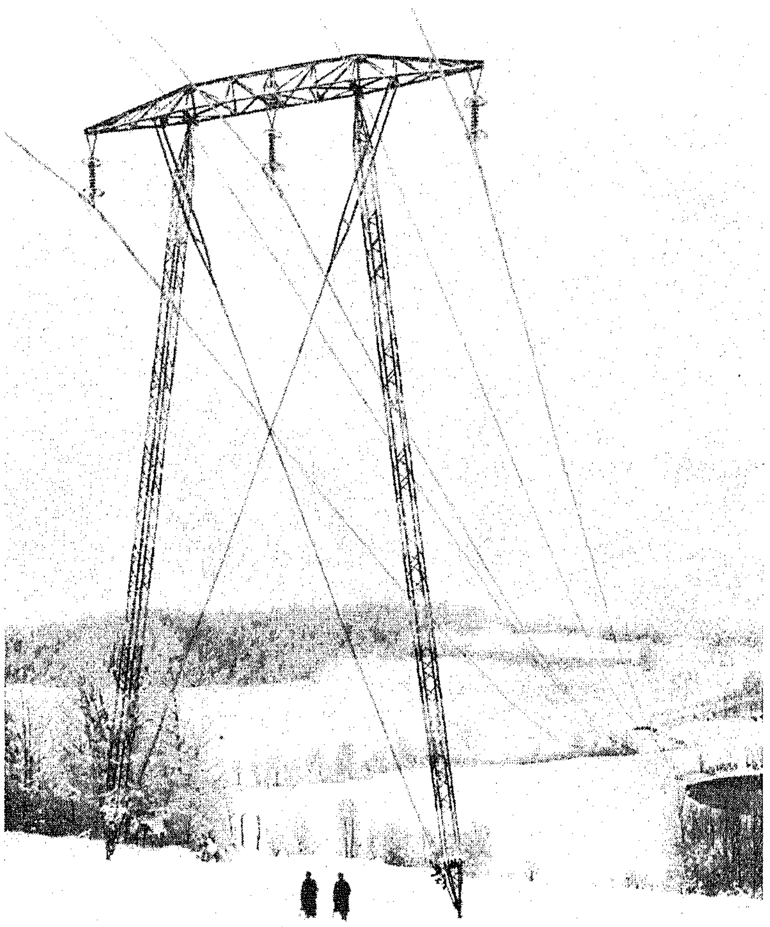

Fig. 4.—Articulated suspension tower for 150-kV line.

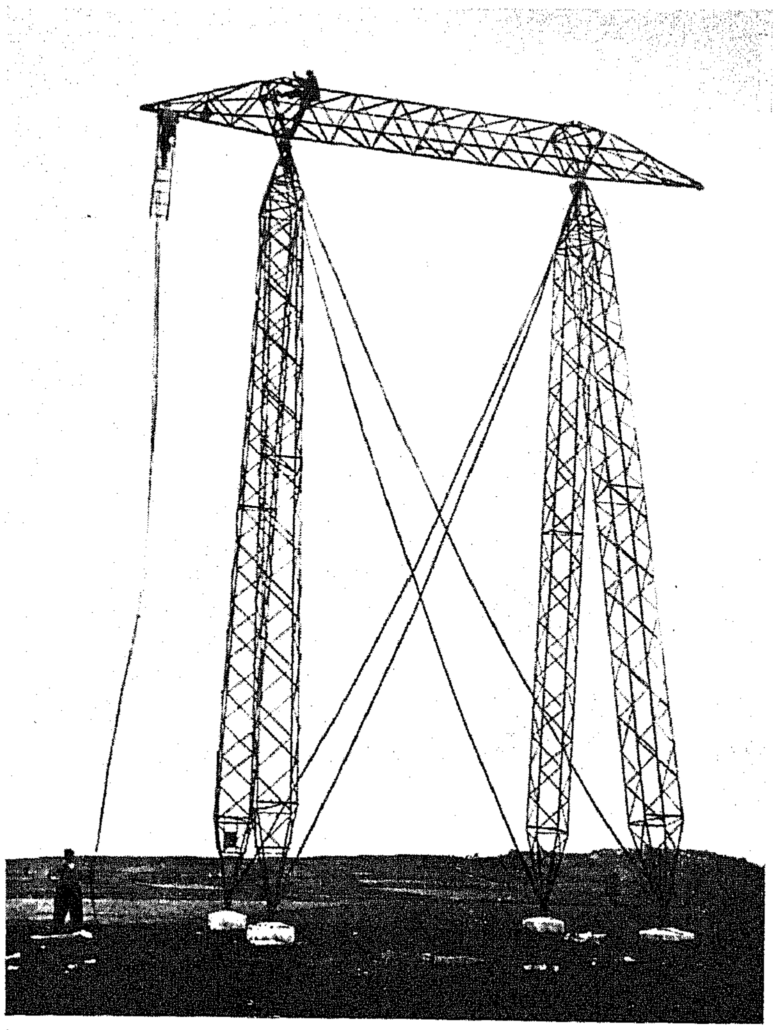

Fig. 5.—New type of tower for 150-kV line.

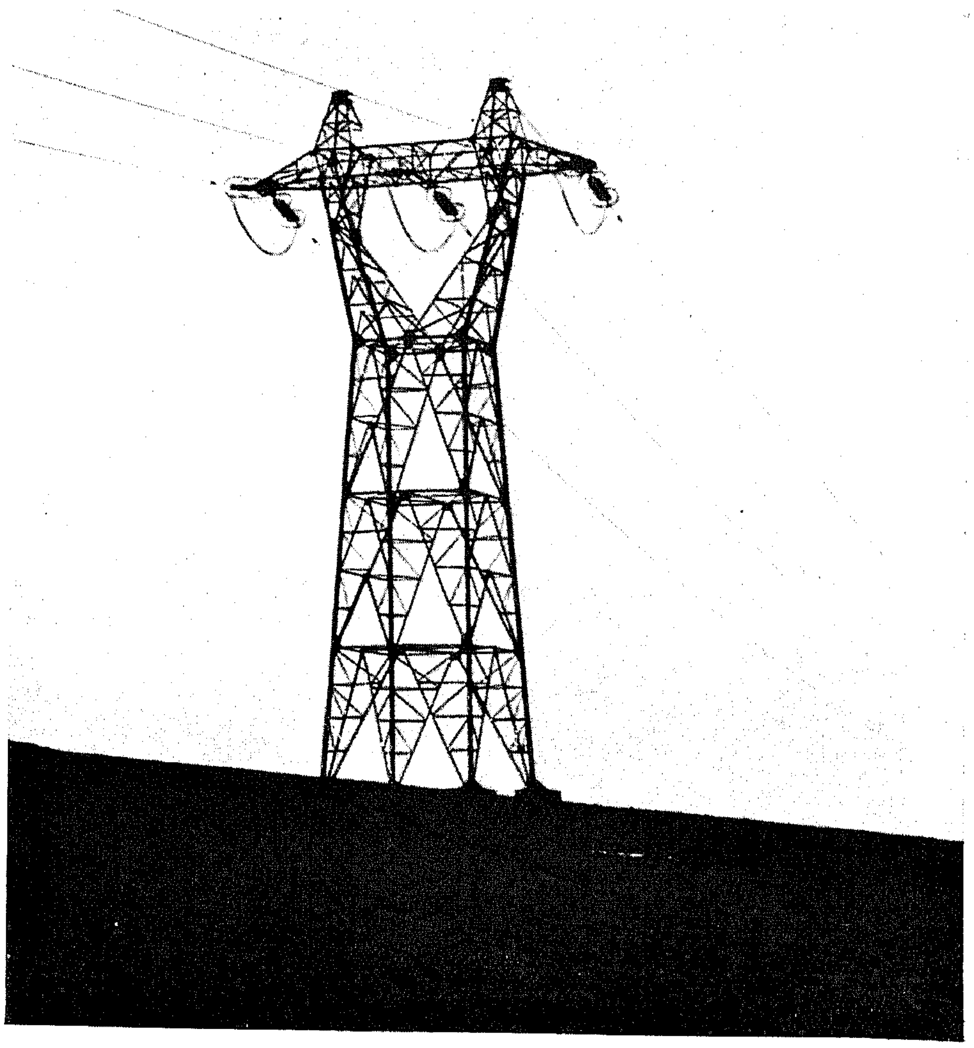

Fig. 6.—150-kV line in a heavy ice-loading district.

RECENT DEVELOPMENTS IN THE TRANSMISSION OF ELECTRICITY IN FRANCE

By P. M. J. AILLERET, Associate Member.

(*Résumé of a Lecture delivered before the* TRANSMISSION SECTION, 29*th April*, 1937.)

INTRODUCTION

At first sight, a map of the French lines operating at voltages above 100 kV (see Fig. 1) shows an interconnecting system similar to the British grid (see Fig. 2). The aggregate length of these lines in France is 4 817 miles,* and the geographical distribution of the lines in the two countries is similar. If, however, we examine these systems more closely we find that, while the British grid has a uniform voltage of 132 kV, the French system includes lines operating at 220 and 150 kV (the new standard voltages), at 120 kV, and even at 110 kV. This difference has arisen for two reasons, the first historical and the second geographical.

HISTORY OF THE FRENCH GRID

The construction of the French grid has proceeded gradually, over a period of 20 years. The first line working at 120 kV dates back to 1920; a few years later it was considered necessary to raise the voltage of the new lines to 150 kV, and the first 220-kV line was put into service in 1932.

Every time it seemed necessary to build a new transmission line the generating companies and distributing companies, and sometimes also the electrochemical industries or railway companies interested in the project, combined together in a special company whose purpose was confined to the construction of that line or of a limited number of others. Every time a new line was proposed which did not interest the same producers, distributors, and industries, as were represented in the existing companies, a new company had to be formed. The whole system was financed by this very flexible method of co-operation between producers, distributors, and important industries, under the supervision of the Minister of Public Works, who has to see that no line wastefully duplicates another and that the lines are developed in such a way that they can finally form a co-ordinated system. Thirty-nine companies have been formed to finance the construction of the lines, and this number is unnecessarily large so far as the operation of the lines is concerned. The responsibility for operation is in fact entrusted to a fairly small number of these companies; it may be said that they are divided into about 10 regional groups, each having its central control board.

INFLUENCE OF GEOGRAPHICAL POSITION

Another reason for the use of several voltages is a geographical one. In France the price of coal varies much more from one part of the country to another than in Britain, because the coal production is practically concentrated in the north, and the centre of France is far from any harbour. Hydro-electric generation is also concentrated in limited mountain areas, and approximately half of the total number of units generated come from this source (7 850 million kWh in 1935, out of a total of 16 375 million kWh). Consumers are also very unevenly distributed. Some regions which are very rich in water power have practically no local consumers; others have an important electrochemical and electrometallurgical load, constant throughout the day but with some seasonal fluctuations, which can be advantageously combined with the usual loads of a distribution system.

For these reasons very large blocks of power have to be transmitted from hydraulic centres to consuming centres. Moreover, the difference of seasonal conditions between the Alps or Pyrenees, where the melting of glaciers gives the maximum power in spring and summer, and on the other hand the lower ranges of Central France, where summer is the dry period, justifies large-scale transmission of energy from one region to another. A voltage of 220 kV, and even double-circuit lines operating at that voltage, have been necessary in some instances for these reasons. Thus the total carrying capacities of the various transmission routes of the French system are very different from those of the British grid.

REACTIVE ENERGY

Though there are large power stations in every region of France, their distribution is less uniform than in Great Britain. For this reason the voltage regulation cannot be done solely by the generators, and rotary condensers are necessary to provide or absorb reactive energy according to the load of the lines. They are especially necessary for 220-kV lines, as the capacitance of such a line provides about 13 000 kVA of reactive energy per 100 miles, and this energy has to be absorbed when the active load is merely floating; at a load of approximately 110 000 kVA the reactive energy absorbed by the magnetic field of the current compensates the reactive energy permanently provided by the capacitance of the line.

The condensers are usually of the synchronous type, with high-speed exciting devices; they produce a very important synchronizing effect in the event of short-circuits, and the conditions of stability permit an increase in the power rating. There are in France 27 such synchronous condensers, of a total rated capacity of

* 1 205 miles of 220-kV lines.
2 934 miles of 150-kV lines.
348 miles of 120-kV lines.
326 miles of 110-kV lines.

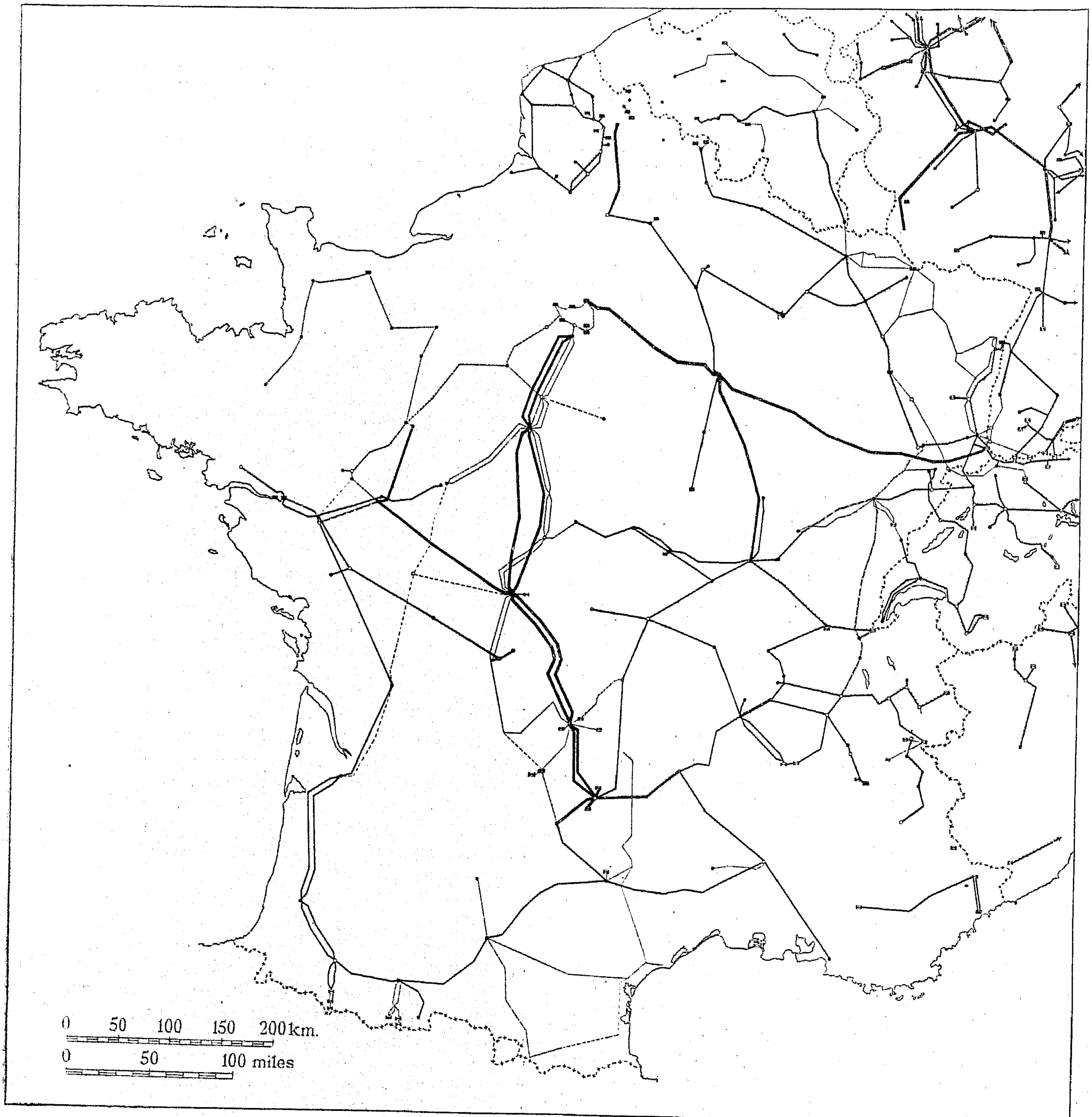

Fig. 1.—High-voltage interconnecting transmission lines in France.

Scale 1 : 1 500 000

220-kV line in operation.

Single-circuit 100- to 150-kV line in operation.

Double-circuit 100- to 150-kV line in operation.

100- to 150-kV line in construction.

Circuits operating at lower voltages are shown by fine lines, but only those which play an important part in interconnection are included.

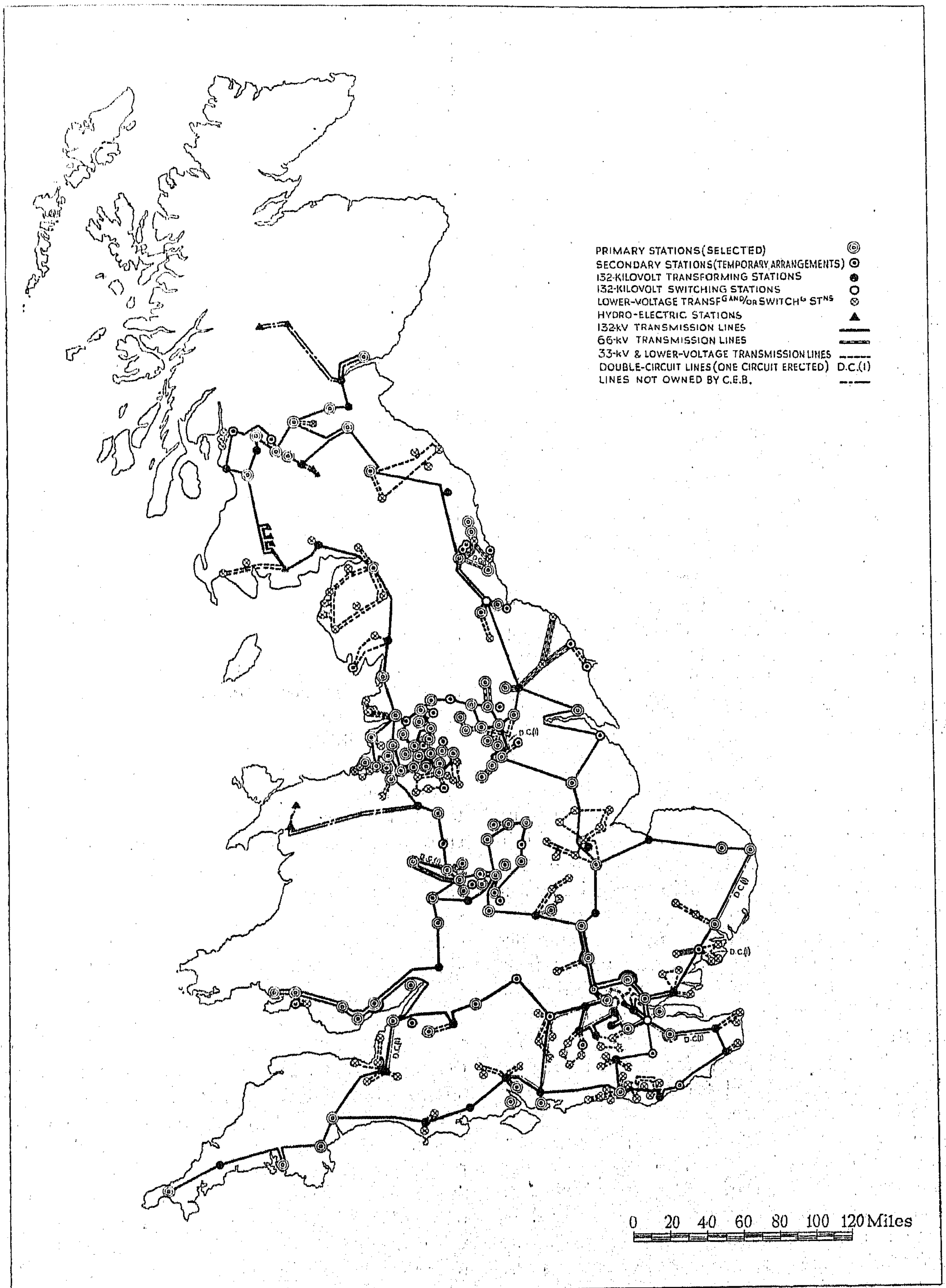

Fig. 2.—The "grid" transmission lines of Great Britain.

400 000 kVA (leading) and 200 000 kVA (lagging). The largest units are of 45 000 kVA. These condensers are usually installed indoors, but one of them is placed out of doors and runs in hydrogen. There are also two asynchronous condensers and 170 000 kVA of reactance coils.

TRANSMISSION-LINE TOWERS

The lines themselves are for the most part carried on towers of the same general type as the British grid towers. Fig. 3 (see Plate, facing page 707) shows such a tower on a 220-kV line with three conductors of 0·635-sq. in. steel-cored aluminium and one steel earth wire. Experiments are being made on other types of towers. For instance, Fig. 4 (see Plate) shows a line carried on articulated suspension towers which are held longitudinally by the conductors and take only transverse stresses. Fig. 5 (see Plate) shows a line carried by towers made of unit lattice beams. The normal tower, of the same type as the British grid towers, seems to be the best except when lightning conditions make more than one earth wire necessary, or when heavy ice loadings are expected. In these cases, towers of the American type are used (Fig. 6, see Plate).

UNDERGROUND CABLES

An 11·5-mile 220-kV underground cable has been found necessary for transmitting the hydro-electric energy from the South-East to the St. Denis power station through a densely populated suburban area. This oil-filled cable is capable of carrying 150 000 kVA; the charging kVA is 65 000.

COMMUNICATION CHANNELS

Communication between substations is effected by carrier currents over the conductors of the extra-high-voltage lines. Most of these transmissions use two wavelengths, one for each direction of speech, but some use only one wavelength. Most of them use only one insulated conductor and an earth return, but some use two insulated conductors. The frequency varies from 45 to 285 kilocycles per sec. Seventy communication channels (counted from each substation to the next one with which it can communicate) are used for telephony; 10 channels are used for interlocking of circuit breakers; and 7 are used for telemetering, but this number will rapidly increase.

The contrast between this and British practice may be partly due to the fact that the French Post Office provides a smaller proportion of underground circuits than the British, and of course overhead telephone lines are never quite reliable. An explanation may also be found in the fact that the distance between substations is greater on the French system, and whereas the cost of a carrier-current system is independent of the distance the cost of a pair of wires is practically proportional to the distance. The distance for which both systems cost the same is between 30 and 60 miles. In actual fact a number of sections of the French lines are much longer than this. The longest length of line between substations is 197 miles, and occurs on the 220-kV line between Creney (near Troyes) and Kembs (on the Rhine).

OPERATION

The French system is not yet operated in one unit. It is divided into a few groups which occasionally can be put in parallel, but by lines of too small capacity to maintain stable synchronism. The number of groups has been rapidly decreased by the construction of new links, and at present the largest group in practically permanent synchronism covers the greater part of France: Paris, Alsace, the Alps and "Massif Central," Western France (Nantes), and South-East France (Marseille), are all in this group. Next year this system will be connected to the Pyrenees and S.W. France system by a line capable of transmitting a large amount of power, and it is probable that permanent synchronous operation will be tried.

Up to this year the interconnected system has been operated according to the classical method of one network only being in charge of frequency control, all the others being responsible for the interchange of power between this particular network and the interconnected system. This method is subject to two difficulties. The first is that, owing to the great amount of interconnected load which exists at present, frequency control is becoming a more and more difficult task. Though the probability is that the total load variation is proportional only to the square root of the interconnected load these variations become too great to be dealt with by one power station or even by two power stations working with interlocked governors. It is therefore desirable to spread the duty of regulating the frequency over all the interconnected networks. The second difficulty is that the load on the interconnected lines shows continuous oscillations, of amplitudes up to 20 000 kW, due to the unwanted operation of the regulating system.

For instance, suppose two networks are exchanging load, the first being in charge of the frequency and the second in charge of the interchange load. If there is a sudden increase of load on the first network, the frequency drops slightly and the governors of the turbines of both systems automatically increase the output of all power stations on their networks. Consequently there is an increase of the power sent from the second network (where the load has not altered) to the first. Realizing this, the operator (man or automaton) of the second network actuates the governors of his network so as to reset the interchange power. Then, when the frequency has become normal again as a result of the actions of the operator of the first network, the governors of the second network automatically reclose their valves. Thus the operator of the second system will have to act again, and stability will not be realized until he has exactly reversed his first action. Of course, these fluctuations would not have taken place if the operator of the second network had done nothing. The governors on his network would have automatically opened and then automatically reclosed to the same extent when the first network brought back the frequency to the standard value.

Two methods may be employed to remedy these useless actions. The first one is an interlock method whereby each of the networks which is in charge of an interchange load is operated according to the following rule: When the power exported by this network in-

creases, the operator has to act upon the automatic governors so as to decrease the production only if the frequency is normal or above normal, and not if it is below normal. When the power exported decreases, the operator has to actuate the governors to decrease the production only if the frequency is normal or less than normal, and not if it is above normal. It is easy to see that with such a rule in force the operator acts only when the trouble is on his own network. Experience seems to show that this method is successful and improves the working of interconnections where a single network is in charge of the frequency control.

The second method, the bias system, seems more promising, as the task of regulating the frequency is equally divided and all the networks play similar parts. Each network regulates a quantity of the form $(f + KP)$—where f is the frequency, P is the exported interchange power—without taking any heed of the frequency itself. Special instruments have been devised to measure such a combination of frequency and power. Considering, for example, only two networks, the first one regulates $(f + KP)$ and the second one $(f - KP)$, P being the power delivered from the first to the second. It is evident that if these two quantities are made equal to the desired values $(f_0 + KP_0)$ and $(f_0 - KP_0)$ then P must be equal to P_0 and f to f_0. Moreover, a simple calculation proves that if the coefficient K is well chosen,* then, if there is trouble on one network, the operators of the other networks are not induced to intervene unnecessarily. It seems that with this bias system, which is in the experimental stage at present, synchronized operation of the various groups of the French system will be possible without useless fluctuations of power and without the necessity of selecting a special network for the increasingly difficult task of controlling the frequency of a continually expanding system.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 29TH APRIL, 1937

Mr. J. R. Beard: The lecturer mentioned that nearly half the electrical-energy output of France is generated from water power: looking up our own figures, I find that last year about 23 000 million units were generated in this country, of which only 750 million (or about 3 per cent) came from water power. The fact that practically all our power is steam-generated complicates our problem of running a unified system, as the loading of the steam stations is varied a great deal more than is that of normal water-power stations. Even our small proportion of water power is subject to variable loading, as a considerable part of it is obtained from the new Galloway scheme where the output is largely used for peak purposes, since storage was difficult and the development of the power itself was cheap.

The long-distance transmission problem has not yet arisen in Great Britain but it may arise in the future, so that the lecturer's description of the French 220-kV system is of great interest. Usually we are inclined to think that America has carried out most of the 220-kV developments, and I do not think the extensive 220-kV developments in France have been fully appreciated. I should like to ask the lecturer to give us some idea of the relative costs of 220-kV transmission. From figures which I have in my possession it would seem to cost practically twice as much as 132-kV transmission, and one therefore begins to wonder whether there is any field for it unless the distances are so very great that it is required for reasons of voltage regulation.

The most surprising thing I have noticed in glancing through the résumé of the lecture is that it makes no mention of lightning. Lightning accounts for about one-quarter of the total troubles that occur on the British grid and for two-fifths of the troubles that occur on the lines themselves. The extent of the troubles which occur differs according to the voltage of the line. On the 33-kV lines lightning troubles are about $2\frac{1}{2}$ times as numerous per mile of circuit as on the 132-kV lines. It would be interesting to know the corresponding proportion which exists in France between 220-kV lines and lines operating at 110 to 150 kV.

We have suffered much from fog and soot troubles, but fortunately means of dealing with these have been developed and they are now becoming almost a thing of the past. I should be interested to know whether such troubles have occurred in France.

Our other main trouble has been contacts of conductors due to wind, snow, and ice. Here again the situation is improving, because the cause of these troubles is usually the crossing of phase conductors and such crossings are being eliminated.

I should like to ask whether double-circuit lines are being much used in France to-day. I understand that on the Rand (South Africa) the use of double-circuit lines has been abandoned owing to the risk of lightning affecting both circuits. By using parallel single-circuit lines this risk is avoided even if the distance between the two lines is quite small.

I should like to conclude by mentioning that many British engineers feel that the real achievement of the grid has not been on the engineering side. The real achievement is that by bringing the grid into being England has managed to lead the world in the national planning of one big industry, the wholesale generation and distribution of electricity.

Mr. J. Hacking: In France, on account of the large amount of water power and the position of the coal mines, it is necessary to transmit substantial blocks of power over long distances. In this country that has not been necessary, and therefore I agree with Mr. Beard that we have not yet had to tackle the transmission problem seriously in this country. The difference in this respect between the two countries is also exemplified by the fact that on the British grid it has not been found necessary to install synchronous condensers or special reactive arrangements.

* For each network the coefficient K must be equal to:—

$$\frac{\text{Normal frequency} \times \text{Average percentage regulation}}{\text{Total power of the generators of the network}}$$

This expression does not vary if the structure of the other networks is altered.

(The term "percentage regulation" here signifies the value of the expression $\frac{\Delta f/f_0}{\Delta P/P_0}$, where Δf is the change in the frequency f_0, and ΔP is the corresponding change in the power delivered by the turbine, the maximum output of which is P_0.)

The tower designs shown by the lecturer are of considerable interest, and I hope that when the lecture is published in the *Journal* it may be possible to include certain of the fundamental dimensions, such as spacing between cross-arms and clearances between live conductors and ground. When he was dealing with the question of sleet the lecturer referred to the specially heavy design of tower illustrated in Fig. 6. The towers in this figure, and also in some of the slides, are shown equipped with tension insulators, and I should like to know whether such insulators are used exclusively on the lines in question.

Has any trouble due to vibration been experienced on the French lines? On the British grid, in view of the experience in other countries, we keep a very close watch on the vibration problem. When we found that certain of our lines were vibrating we installed a large number of vibration dampers of the Stockbridge type, which have the effect of preventing such vibration completely.

I should like to ask the lecturer whether the French supply engineers have adopted any definite policy as regards the maximum short-circuit kVA for which they should design their breakers. In the early days of the construction of the British grid we decided that all the main breakers should be designed to deal with a rupturing capacity of 1½ million kVA. This was the maximum rupturing capacity commercially available at that time, and so far we have not found that it imposes any serious limitation. I should be glad to know whether, on the French system, similar figures have been adopted.

What is the opinion of the lecturer on the trend of circuit-breaking development in France? In this country we have concentrated on the use of relatively large oil-content circuit breakers, whereas in France experiments have been made with gas-blast and other breakers. What is the lecturer's opinion as to the relative merits of these devices? Also, what policy has been adopted in regard to the use of lightning arresters at the French terminal substations?

I should like to ask what is the practice followed in regard to the earthing of neutrals on the 220-kV systems in France. In this country we have adopted the policy of solid earthing, but on the Continent there has been an ever-increasing use of Petersen coils, which have particular value in that they prevent interruptions of supply due to lightning.

The bogy of frequency control rather worried us in the early days of the grid, and many engineers considered that parallel running of such large sections would be quite impossible. In actual fact, however, we have not run across the difficulties to which the lecturer referred. This, I think, must be due to the fact that the fluctuations in load which we get in this country are less than those which occur in France.

The lecturer mentioned that the total interconnected load of the biggest section of the French system to be run in parallel is 2 000 000 kVA. The biggest grid area in this country, namely S.E. England, is always run as a whole in parallel, and the maximum demand is over 1 700 000 kW. It is also quite common practice to run the S.E.E. Area in parallel with three or more of the other areas. There have been occasions on which we have had over 4 000 000 kW of interconnected load, and as many as 150 generating stations working in parallel. In general, however, the practice is to divide the country up into areas, each of which runs isolated from the other systems. In the smaller-loaded districts we have found no difficulty in leaving the frequency control to one of the larger stations. This practice, however, has the disadvantage that the station has to be of big capacity and therefore one which it is more economical to run as a base-load rather than a peak-load station. In bigger areas we have had to avoid this method of frequency control, but we have been able to carry out satisfactory frequency control by leaving the loading in the hands of one load-despatcher in the central control room. In the S.E.E. Area the frequency very rarely varies by more than 0·1 cycle per sec. from the mean value. As a further indication of the excellence of the frequency control, I would mention that it is very rare for the accumulated error of the synchronous-motor clocks connected to the system to exceed 5 seconds.

Mr. W. Fennell: I should like to ask whether the suggested method of controlling the frequency with reference to the interchange power would prevent the running of the system with constant frequency for the use of clocks.

As regards the washing of insulators, in my opinion the type of insulator installed should be designed to stand up to the conditions of the country in which it has to operate; the washing of an insulator is an admission of defeat in the design of the insulator for those conditions.

We in this country are beginning to be rather afraid of the large-tank circuit-breaker holding hundreds of gallons of oil. When this type of equipment is installed a great deal of money has to be spent on conduits to carry the oil away and on sumps to prevent it overrunning the countryside when it does go down the conduits. I should be delighted to hear of the entirely successful development of a substitute for this type of breaker.

I should like to press the lecturer a little further on the performance of the particularly interesting circuit breakers that we saw during the visit of this Section last summer at Creney.

Major T. Rich: The transmission lines described by the lecturer all run from the places where water power is cheap, and in many cases unusable, to places where there is a demand for electric power. The principal coal area is in the Pas de Calais, and I notice that electric power is not being transmitted to Paris from that area. Evidently, therefore, it is cheaper to convey coal from the Pas de Calais to Paris than it is to generate the power on the spot and transmit it electrically.

I am very interested in the question of flexible conductor supports. Flexible towers were introduced by M. Darrieus, of Paris, about 10 years ago, and I am astonished that they have not been used in other countries besides France and Algeria. The cost and the rapidity of construction are a great feature of these towers, which are so designed that the stresses in them can be easily determined.

Mr. G. H. Fowler: Are any voltage-regulation troubles experienced on the French transmission lines?

As there is a considerable amount of synchronous power-factor-correcting plant connected to the network, it would appear that load fluctuations must also cause power-factor fluctuations. What form, therefore, does the voltage regulation take? This regulation is presumably quick-acting, and I should like to know whether, combined with the quick-acting frequency control which is installed, it causes momentarily unstable conditions to be set up.

Mr. F. Jervis Smith: I notice that the main power lines in France follow very closely the network of communications of the French Post Office; I should like to ask what form of liaison the power transmission companies have with the Post Office for the discussion and mutual adjustment of troubles due to interference with communication networks.

Mr. W. E. Highfield (*communicated*): The facts and the conditions of electric transmission in France are so totally different from those prevailing in England that hardly any useful comparison between the two is possible. Practically all that can be said is that in both countries electricity is sent at high voltage by overhead lines; and thereafter, except for details of construction, the two systems differ as widely as may be possible.

France, with her three distinct sources of power widely separated from each other, must transmit great blocks of energy over long distances in order to take full advantage of these gifts of Nature. Her system is and must remain a transmission system. On the other hand, the grid in England, with concentrated loads in the manufacturing centres which merge into one another and threaten to become continuous, has become a distribution system. One may almost liken it to a continuous bus-bar with reactance between the sections. Nevertheless, there is one fundamental feature of the two systems which must be noted. In France the control appears to be vested in some ten authorities working by voluntary agreement: in England the control is vested in one authority with statutory power. The very core of either scheme lies in the control, and it is absolutely essential for success that this should work smoothly.

Referring to the engineering side, a study of the double-earth-wire towers will convince one that France has given no overriding commission to an expert in architectural beauty. The designs of Figs. 4 and 5, however, have no doubt been dictated by considerations of transport and erection as well as by electrical considerations.

English engineers will be deeply interested in the 220-kV cable and the rotary condenser run in hydrogen, and will admire the boldness of their French colleagues in adopting these innovations. Hydrogen has been proposed as a surrounding medium for turbo-alternators, but no scheme of this sort has been carried out as yet. France has once more got ahead of us, and at a point where one would not have expected it, for if any country has good reason for protecting machinery from its native air surely it is England.

In a grid transmission system there are thousands of towers with millions of bolted joints. There are thousands of miles of conductor with probably three mechanical joints to the mile, and there are some millions of insulators each dependent on careful erection and adjustment. Now the men who put up this mass of complicated work are not skilled in the sense that they first serve an apprenticeship in the art. They are labourers taken from town and village and trained in the field as the work goes on. Yet I do not think there is a single instance of a tower failure, and the number of other defects has been so trifling that I say that these grids—in France, England, and elsewhere—are a monument to the native skill and integrity of those who put them up.

Mr. P. M. J. Ailleret (*in reply*): Mr. Beard stresses the fact that the problem of running a unified system is complicated in England by the small importance of the hydro-electric stations, due to the loading of the steam stations being varied a great deal more than that of normal water-power stations. In point of fact, water-power stations which have no storage facilities are always used as base-load stations, and consequently their load is quite constant; on the other hand, the majority of the modern French power stations have considerable water-storage capacity and are therefore used as peak-load stations. The combined operation of water and steam power stations tends to confine the production of the steam stations to dry and cold periods. Thus the output of the steam stations may exhibit a seasonal variation, but, as most hydro-electric stations can concentrate their production at the peak periods, the steam stations have a tendency to be used more regularly throughout the day. For this reason the exchange of power between water and steam stations is very irregular, and tends to complicate the problem of running the system. The curve representing the combined load of all the power stations is determined by the consumption of energy and is therefore of approximately the same form for both England and France.

Double-circuit 220-kV lines have not been in very great favour in France during recent years, since the clearances which are necessary between conductors at 220 kV do not permit an easy construction of towers carrying two circuits. When two circuits are necessary they often take the form of lines a few hundred feet apart, but the tendency is to run them on two different routes very far apart, so as to eliminate the possibility of simultaneous lightning troubles. Similar remarks apply to 150-kV lines, though in some cases, chiefly in densely-populated areas, double-circuit towers have been used. It is not the practice in France to do maintenance work on 150-kV circuits with the lines alive, as is done in the U.S.A., and this is a further advantage of separate towers.

Fog and soot troubles are practically unknown in France, and it is not necessary to wash the insulators.

Lightning is the chief cause of trouble. It is difficult to answer Mr. Beard's question as to the relative frequency of lightning troubles on 150-kV and 220-kV lines, as local conditions differ from one part of France to another and the value of the tower earthing resistance is not the same on all lines. When lightning strikes an earth wire or a tower, the line flashes-over and there is an outage only when the drop of potential at the earthing point is greater than the value the insulators can withstand. We generally use 10 insulators (10 in. diameter) on 150-kV lines, and 15 insulators on 220-kV lines; but 220-kV lines are, on the average, more carefully earthed than 150-kV lines. These two reasons combine to explain

why the frequency of trouble, for the same mileage of line, is much less on 220-kV than on 150-kV lines. It is not, however, possible to give a reliable estimate of this difference.

Figs. A and B answer Mr. Hacking's question as to the the towers on hilly ground are chosen so that the question of clearances does not enter into consideration: the average span on this line is 1 377 ft. Fig. B refers to a 220-kV line (Henri-Paul to Creney). This type of tower corresponds to a span of 1 312 ft. from the point of view

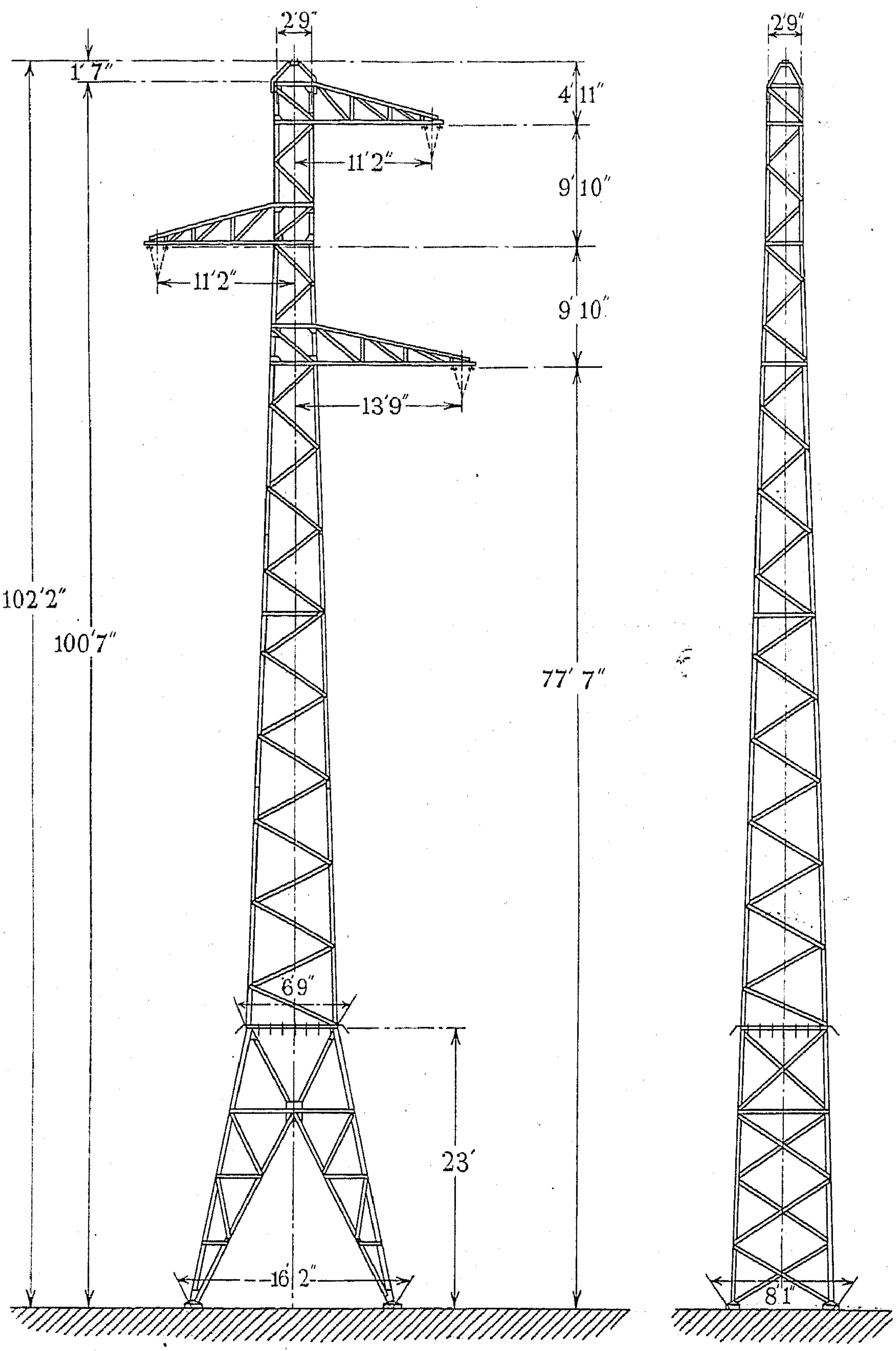

Fig. A.—150-kV line (Sautet–Grenoble).

fundamental dimensions of the towers. Fig. A refers to a 150-kV line (Sautet–Grenoble). The height of this type of tower corresponds to a span of 1 148 ft. on horizontal ground, with a clearance of 29 ft. 6 in. above the ground at mid-span at the maximum temperature. Its strength is sufficient for a span of 1 394 ft. when the positions of of clearances above horizontal ground and to a span of 1 558 ft. from the point of view of the strength of the tower: the average span on this line is 1 443 ft. According to the regulations the clearance must never be less than 19 ft. 8 in. above fields and 26 ft. 3 in. above roads. Mr. Hacking points out that the towers shown in Fig. 6,

and also in some of the slides, are equipped with tension insulators. This is only a matter of chance in the choice of photographs: the proportion of suspension-insulator towers on such lines is only just above the usual value.

Stockbridge damper is very effective in suppressing the vibration.

The trend of circuit-breaking development is towards the use of breakers without oil, or with a comparatively

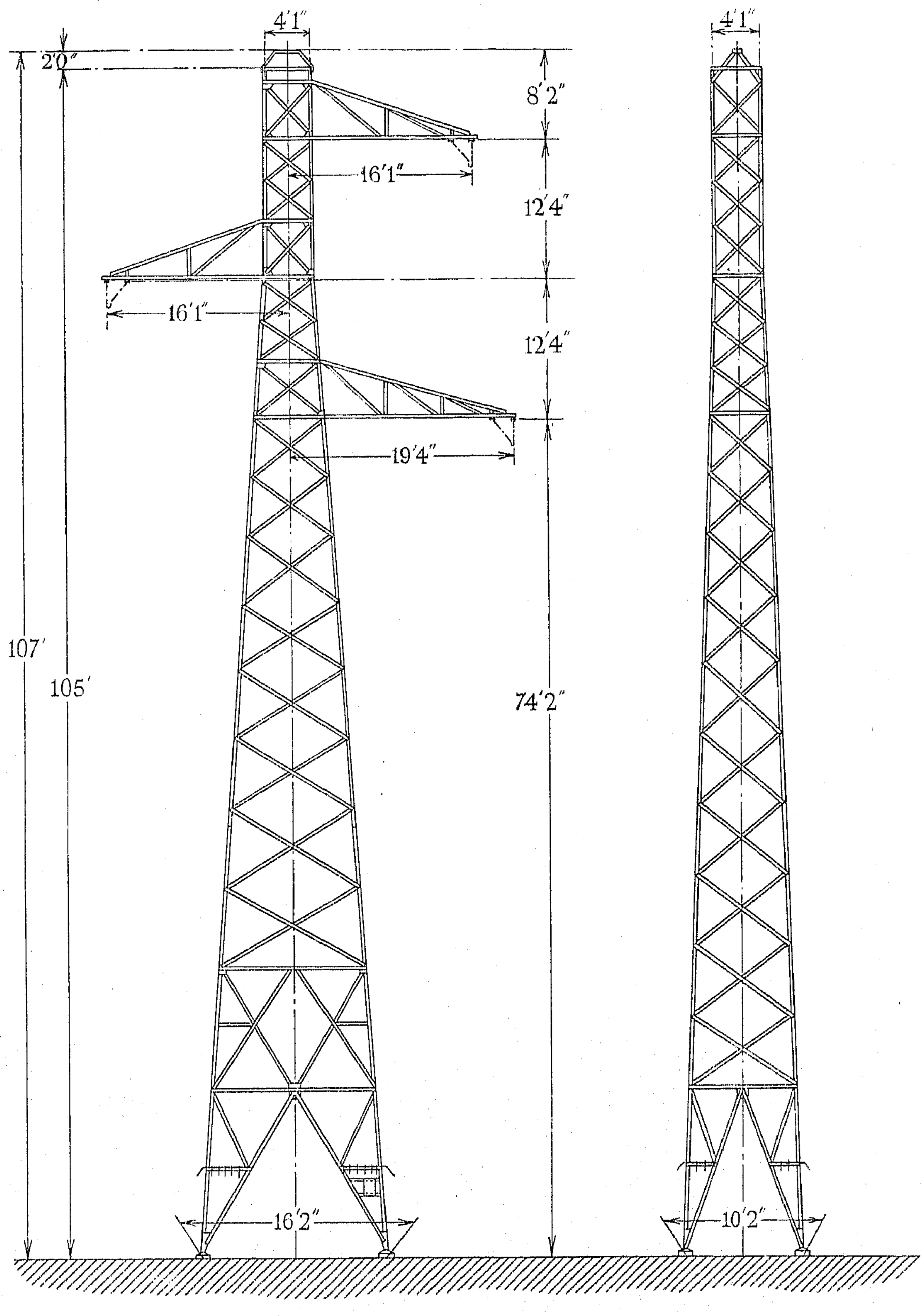

Fig. B.—220-kV line (Henri-Paul to Creney).

Stockbridge dampers have been used on those sections of the French lines where vibration troubles have been experienced, but lines have never been systematically equipped with dampers at the time of their construction. Vibration recorders clamped to the lines and registering the vibration during a fortnight have shown that the

small quantity of oil. Most breakers recently installed on 150-kV and 220-kV lines are of this second type. Their rupturing capacity is usually either 1 000 000 or 1 500 000 kVA for 150-kV breakers and 2 500 000 kVA for 220-kV breakers. Lightning arresters are not used on extra-high-voltage lines and substations; earth wires are usually

placed above the substation to take charge of any direct stroke. It is considered sufficient to maintain co-ordination between the insulation levels of the transformers, busbars, and line; lightning arresters are not regarded as indispensable. On the 150-kV and 220-kV systems the neutral is usually directly earthed. Petersen coils are not as extensively used in France as they are in Germany.

In France as well as in England the accuracy of frequency control, as regards both frequency itself and also the integrated frequency, is very much in excess of the consumers' requirements. The only advantage of this very high accuracy is that it helps to prevent fluctuations of power in the interconnecting system. From this point of view combined control of frequency and interchange-power seems to have great advantages and will facilitate the extension of the areas run in synchronism.

Replying to Mr. Fennell, the integrated frequency depends upon a special control the operation of which can be very slow. It is therefore quite independent of the method of controlling the instantaneous value of the frequency. On a system controlled by the combined frequency and interchange-power method it is very easy to superimpose a slower control maintaining the error of synchronous clocks within a few seconds.

In reply to Mr. Fowler, no special difficulty is experienced in regard to voltage regulation. The synchronous condensers give ample facilities for regulating the voltage, and there are also a number of tap-changing transformers, though in proportion to the total number of extra-high-voltage transformers these are less numerous than in England. The synchronous condensers are usually automatically regulated so as to maintain constant voltage at certain points of the network. They are equipped with quick-acting devices which help to maintain stability in the event of trouble endangering the synchronism of the system.

It is very difficult to answer the question of Mr. Jervis Smith on interference with communication channels. Though the main power lines follow in many instances the same general routes as important telephone circuits, they can generally be located at a sufficient distance to prevent excessive interference. This is, however, impossible in some cases, e.g. in the narrow valleys of mountainous districts. In such circumstances special precautions have to be taken; for instance, insulation of the neutral with instantaneous action of the relays. Interference difficulties are usually overcome by mutual agreement following consultations between representatives of the Post Office and of the power transmission authorities. Where agreement cannot be reached the measures to be taken are settled by a joint decision of the Ministry of Posts and Telegraphs and the Ministry of Public Works, the latter having the same powers in France as the Electricity Commissioners have in England.

DISCUSSION ON
"FIRE PRECAUTIONS IN MAJOR ELECTRICAL STATIONS"*

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 16TH MARCH, 1937

Mr. J. H. Haws: The paper appears to concentrate almost entirely on new designs and does not deal with the problems associated with existing substations. In the case of an existing station there is considerable difficulty in rearranging the buildings in order to sectionalize the apparatus into separate chambers.

There is one small criticism which I should like to make in regard to Fig. 3. This shows oil sumps outside the building: these might very quickly fill with rain water, and the system would not then drain away the oil in the event of a fire.

Considering existing undertakings, there are certain features which affect the fire risk. One is the provision of busbar protection, and another is routine testing of installations. I should like to know how these features affect a decision to incur the heavy expense of the special construction work which is necessary. Does the author consider that it would be necessary to redesign the whole system of an existing undertaking with a view to bringing it in line with modern practice?

The reduced-temperature conditions should be taken into consideration when CO_2 is released in large quantities. I have heard of a case where a 6-in. pipe-line was frozen and a valve was damaged owing to CO_2 being released in the building, and where in addition a pump was put out of commission by the freezing of water in it. What is the author's opinion on this point?

I should like to refer to the possibility of using fireproof canvases for isolation purposes in place of brick walls, sliding doors, etc. Such canvases are used in mines, etc., generally for ventilating purposes; they serve to confine the CO_2 to the area affected, and render it possible to use a smaller quantity of CO_2 to obtain the concentration required.

Does the author know of any case where an oil switch has been subjected to CO_2 and has suffered damage, due, for example, to oil becoming frozen and preventing the switch from operating?

Mr. J. R. P. Lunn: The transformers illustrated in the author's slides are all shown housed in brickwork; I should like to know why he does not use weatherproof transformers and stand them in the open, where the cooling conditions are much better and the transformers will keep much freer from dust. If a transformer standing in the open should take fire it is hardly likely to do as much damage as one inside a building, provided, of course, it is not too near other transformers. In many large power stations the works transformers are placed outside the buildings, and most of the C.E.B. transformers stand in the open. For many years our practice has been to make the substation buildings only large enough to house the switchgear and to use outdoor transformers, and so far we have not found any reason for discontinuing this practice.

[The author's reply to this discussion will be found on page 720.]

FURTHER CONTRIBUTION TO THE DISCUSSION BEFORE THE INSTITUTION

Mr. J. R. Brookman (Australia) (*communicated*): In the official report of the Electricity Commissioners on the fire at the Bradford (Valley Road) generating station appears a statement to the effect that protective relays for isolating a faulty busbar from the rest of the system are not in general installed by electricity undertakings in Great Britain. Confirmation of this statement will be found in the E.R.A. Report Ref. F/T 94,† which indicates that very little attention has been given to the subject of busbar protection. This is rather surprising, seeing that nowadays overload protection is not provided on generating plant in large power stations, and that a fault on the busbars would have to be cleared by manual operation of control switches by a switchboard attendant. Owing to its duration a fault under such circumstances is liable to cause extensive damage.

Mr. Winfield's paper discusses the protection of busbars by leakage relays operated from current transformers connected between the lightly insulated switchboard frame and earth, and arrives at the conclusion that such apparatus is of doubtful utility and liable to cause unnecessary interruptions of supply. That this apprehension is unwarranted is evidenced by the excellent record which this type of protection has achieved during the past 14 years in the major substations of the Adelaide Electric Supply Co.

When the Company's 33-kV transmission system and ring main were constructed in 1921–23, outdoor substations were adopted, and the busbars and isolating switches were mounted on galvanized-pipe frameworks supported on concrete pillars about 3 ft. high. Both the 33-kV and the 7-kV busbars were sectionalized by circuit breakers, and the pipe framework was correspondingly divided. Each section of framework was earthed through a leakage current-transformer. The 33/7-kV transformers were included in the leakage protection by earthing them to the framework of their section. Either a transformer fault (to frame) or a busbar fault would open the incoming 33-kV line breakers and the 33-kV and 7-kV section breakers in about 15

* Paper by Mr. F. C. WINFIELD (see page 289).
† *Journal I.E.E.*, 1936, vol. 79, p. 541.

cycles. Non-automatic air-break switches only were provided for the transformers, as it was agreed that the reliability of modern transformers was such that the risk of losing half the substation in case of a failure was a reasonable risk to accept. Core-type 3-phase transformers were used, and it was assumed that a fault in the windings would rapidly develop into a fault to frame and so provide clearance through the leakage protection.* In the nine transformer faults which have occurred (most of them bushing failures) this reasoning has been justified. A description of the transmission systems and the type of relays adopted has been given elsewhere.†

Table A

Analysis of Busbar Leakage-Relay Operations

Year	Relay operation correct	Relay operation inaccurate
1923	—	—
1924	6	2
1925	—	—
1926	8	—
1927	5	1
1928	9	2
1929	5	1
1930	6	1
1931	9	1
1932	6	—
1933	5	—
1934	4	—
1935	2	—
1936	—	1
1937	3	1
Totals ..	68 (87 %)	10 (13 %)

The Company now have sixteen major substations, containing 46 transformers totalling 50 000 kVA, with busbars protected in the manner described above. Ten of these substations, with eighteen 600-kVA 33/7-kV transformers, were put into commission in 1923, and the others have been added from time to time. Some of the later substations are of the indoor type with metal-clad or cubicle-type switchgear. The approximate number of substation-years covered by Table A is therefore 182, the number of transformer-years 448, and the number of leakage-relay-years 364.

The inaccurate operations, i.e. those in which the relay operated when it should not have done, are explained as follows:—

(1) A workman was using a d.c. electric drill on the switchgear framework when a fault occurred in the drill, and the d.c. surge passing through the earthing current-transformer caused the leakage relay to operate. The earth wire to the drill was found to be broken (1931).

(2) A fault on one section of a substation caused both relays to operate. It was found that the two sections were connected together by reinforcing rods in the concrete in contact with holding-down bolts of the switchgear. This type of incorrect operation occurred twice before the trouble was eliminated (1929, 1930). A search coil was finally used to locate the path of the current. All substations are now tested regularly, to make sure that sections are not interconnected

(3) A workman allowed a piece of timber to fall against a leakage relay and trip it (1937).

(4) The remainder were caused by relays tripping owing to vibration or to faulty latching.

It will be observed that there have been no failures to clear under fault conditions. The incorrect operations due to vibration are avoidable in future installations by the selection of suitable relays.

Even with a number of old-type relays in use, the accuracy of the busbar leakage-relays is 87 % (see Table A) for the 14 years covered by the records, while for the past 5 years it is 91 %. These figures compare very favourably with those for the various other types of protection mentioned in Table B.

The method of expressing the accuracy of relay protection in Tables A and B differs from that adopted in the E.R.A. Report Ref F/T 94 in that the accuracy is expressed as a percentage of the number of operations plus failures to operate. I consider this method to be preferable to the one used in that report, because inaccurate operations are shown as a reduction of protective efficiency. Nothing less than 90 % efficiency should be accepted from a modern protective system, and the only type of protection in Table B to reach

Table B*

	Correct operations		Failures to clear fault		Incorrect operations		Remarks
	Number	Percentage	Number	Percentage	Number	Percentage	
Generators	27	56·5	4	8·3	17	35·5	
Transformers	270	68·5	10	2·5	115	29	
Busbars	74	90	0	0	8	10	Overload protection predominating
Feeders	3 929	86·5	74	1·6	535	11·8	

* Calculated on the same basis as Table A from data given in Tables 2, 5, 11, and 12, of E.R.A. Report Ref. F/T94.

* The fitting of Buchholz relays to transformers in major substations is now under consideration.

† *Journal of Institution of Engineers, Australia*, 1935, vol. 7, p. 160.

this standard is the busbar protection. Various methods of protection, including leakage protection, were used. From Table A it is evident that, with careful selection and installation, there need be no hesitation in providing leakage-protection relays for the busbars of generating stations and major substations.

Leakage protection has the following advantages: (a) It is unaffected by "through faults." (b) It is instantaneous in action, thus minimizing fire risk, damage to plant, and disturbance of the system. (c) It is simple of application, particularly in new installations. (d) It is easily maintained at full efficiency. (e) It has no cumulative effect on the time-delay settings of other relays on the system. (f) It has a high degree of reliability. (g) It is inexpensive to install.

The following are the requisites of successful installation and operation. The leakage current-transformer should be suitable for the fault current to be dealt with. Bar-primary types are preferred, with a current rating of about one-fifth of the calculated fault current. Insulation for 600 volts is adequate for a 33-kV system. The relay should be a robust type, not affected by vibration or rough usage. It should have a heavy setting, i.e. $2\frac{1}{2}$ to 5 amps., as under these circumstances there is less chance of tripping due to stray currents. Lighting and power circuits should be kept well clear of the switchgear. Concrete provides sufficient insulation, but care must be taken that holding-down bolts are separated by at least 1 in. from reinforcing rods. If they are very close together they should be separated by some suitable insulating material, or the bolts can be insulated from the frame. A high insulation resistance is not necessary, any value over 10 ohms to earth or between sections proving satisfactory in service. Metallic sheathings of control cables need attention to avoid interconnection of sections. Lead sheaths of feeder cables must be insulated from switchgear. If separate cable terminal-boxes are used they also should be insulated from the switchgear. The earthing leads of cable sheaths and terminal boxes should be connected to the same earth plates as the switchgear, so that in the event of a fault causing a rise of potential due to earth resistance the potentials of the switchgear and of the cable sheaths will rise together. Cable terminal boxes should if possible be placed so that an arc in them will not spread to the switchgear. This is, of course, not possible with metalclad or cubicle-type switchgear, so that there is a certain amount of overlapping between the feeder protection and the busbar protection in such cases, and a fault in a terminal box, which is strictly a feeder fault, will cause the busbar relay to operate. This same overlapping feature occurs in the breaker itself. A fault in a bushing on the feeder side of a breaker will operate the busbar relay, although the fault could be cleared by the opening of the breaker by the feeder relays. Usually, however, the arc spreads to other bushings on the busbar side of the breaker, so that the busbar relays would operate in any case and the disadvantage of "overlapping" on the circuit breaker is negligible. Each section breaker frame has to be electrically separated from the frames of the adjoining sections, and its earthing conductor is taken through two current transformers, each of which is connected to the leakage relay of an adjoining section so that a fault on the section breaker will trip both sections, as shown in Fig. G.

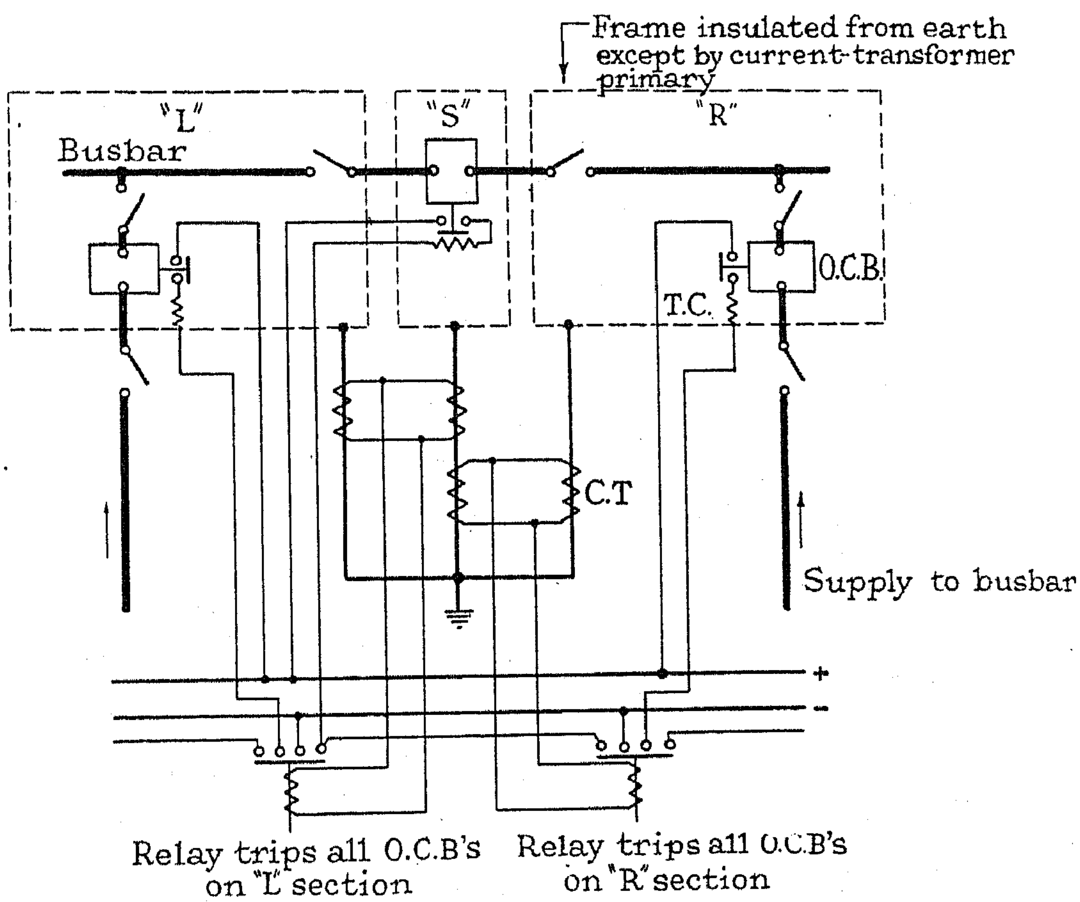

Fig. G.—Busbar leakage protection.

If, in order to avoid accidental tripping of breakers, two relays in series are adopted, as proposed in Mr. Winfield's paper, they must be so arranged that neither of the relays will connect all the circuit-breaker trip coils in parallel when tripped individually. Otherwise the operation of a control switch or some other relay intended to open only one of the breakers would bring out the whole section, if the busbar relay so connected happened to be in the tripped position—either for maintenance purposes or through tripping inadvertently and remaining so unnoticed. The use of two relays in series, however, is to be deprecated, as each extra contact placed in a tripping circuit is an additional hazard. The real solution lies in the provision of relays with a high degree of stability. Fig. H indicates in somewhat exaggerated fashion what is required. Where toggles are used they should be set well over the dead centre. The latch should be strong but light, so as to reduce inertia. To test the latching, the relay is mounted on a wooden board which is rapped sharply with a hammer for a minute or so, and it is noted whether the latch tends to creep "out" or "in." Each relay should be thus tested before installation. No external knob or button should be provided for tripping the relay. The resetting device also, must not be capable of tripping the relay. Where small tripping batteries only are provided, they must be adequate for tripping all breakers simultaneously on two adjoining sections.

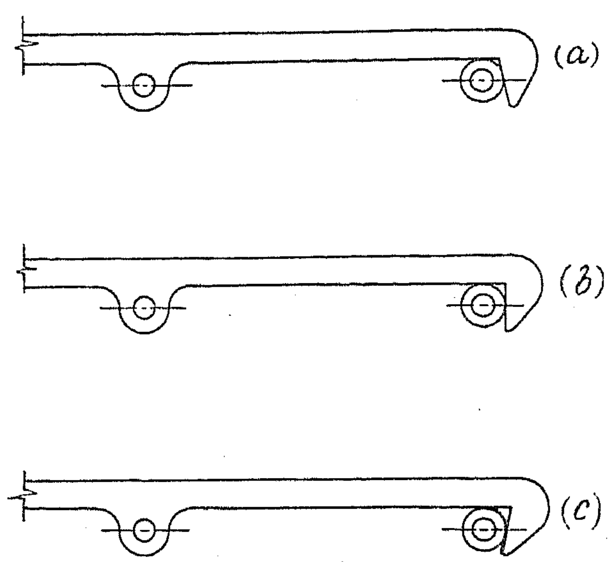

Fig. H

(a) Defective latching. (b) Unstable latching. (c) Positive latching.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, LEEDS, MANCHESTER, BIRMINGHAM, AND MIDDLESBROUGH

Mr. F. C. Winfield (*in reply*): Much of the discussion at the various Centres resolves itself into agreement on points made in the paper, and it would seem unnecessary to make further reference to these. Further, many points made by various contributors are adequately dealt with in the remarks of other commentators. From the remainder it is possible to pick out a number of basic points around which most of the discussions have largely turned, and to these I propose to attempt a collective answer.

Open-type versus Metalclad Switchgear

Much of the discussion concerns the nominal advantages of air-blast and expansion circuit-breakers as opposed to the oil-switch type, and in particular the metalclad form of the latter. Since the paper was written the expansion switch appears to have fallen into disfavour on the Continent and seems likely to be entirely superseded by the air-blast type. The air-blast switch has now passed the early teething stage and is available as a sound circuit-breaking device covering a wide field of use. It possesses, in my view, a single outstanding advantage, and several important disadvantages. The outstanding advantage is its freedom from inflammable insulating material. Its disadvantages lie in the presence of unprotected insulation and particularly in its unsuitability to adoption in the metalclad form of switchgear.

No circuit breaker can properly be considered alone. It forms a single item, albeit an important one, in an assembly which must be considered as a whole. As a pure circuit-breaking device there is nothing that can be done by an air-blast circuit breaker that cannot be done at least as well by circuit breakers of the oil type, and probably better, since the hydrogen resulting from oil is inherently a more suitable medium in which to interrupt an arc than air.

The decision to employ this form of circuit-breaking device in a switchgear layout must then turn solely on the advantage it possesses in the absence of inflammable insulating material. If this feature is accepted by the designer as the fundamental in his switchgear arrangements, then it necessarily follows that he must accept also the extension of the principle to the remainder of the switchgear equipment and must adopt open-type switchgear, for without the use of oil and compound the present use of commercial metalclad switchgear is not practicable.

The disabilities of open-type switchgear, at least for indoor use, lie in the freedom of access which it provides to interference from external agencies (human, animal, etc., and dirt and moisture), in contagious spreading of arcs due to ionized vapour and the explosive forces associated with this, and in the difficulty of direct interlocking and liability to error in operation or maintenance, all of which imply danger to life and to the reliability of supply. Added to this are the large spaces required and the very real difficulty of securing large sites in urban areas. It is perhaps not often realized that probably 75 per cent at least of important switching centres in this country occur in urban areas.

Some 35 years ago the appreciation of these difficulties and troubles with open-type switchgear led to the development of the metalclad type, which progressed in this country as its merits were realized until it now occupies a predominant position except for 132-kV outdoor work, where, for the present at any rate, prime cost reacts too heavily against it.

It appears to me, therefore, that the protagonists of open-type switchgear would propose to select a switch-

gear arrangement because of an outstanding advantage in one feature secured at the cost of a number of others, and that this cannot be sound practice unless that feature is of overriding importance.

Neither from experience nor in fact do I consider the fire risk of transcending importance. The fire risk is a rare contingency requiring, and amenable to, straightforward treatment in design, whereas many other features are bound up in the day-to-day operation of switchgear. I feel strongly that undue stress is being placed on the single aspect of fire risk because of one or two unfortunate experiences associated with inadequate provision for such contingency. The contribution of Mr. Trencham on this matter expresses very well my general views on the subject, and it is perhaps worth while to recall that the long-time interruption of supplies in New York last year resulted not with metalclad switchgear but with phase-isolated open-type gear in which oil-switch fires did not arise.

Some commentators suggest that the cubicle form of gear is fireproof, but such a statement ignores the fact that practically all cubicle gear is open on one side to a common longitudinal passageway and is subject to all the possibilities referred to above. There is no reason other than cost why metalclad gear should not be enclosed in cubicles to secure the best of both worlds. Practical experience, however, indicates that the risk is too small to justify the cost.

I give below a summary of past experience of fire risk on a large system, which stresses the rarity of serious fire and the unbalanced emphasis which is being placed on this risk at the present time. Mr. Kidd's and Mr. Clothier's contributions should also be noted in this connection.

The switchgear and transformer records were examined of a very large mixed system over a period of 18 years. The system includes switchgear and transformers up to 66 kV, the former mainly metalclad but with considerable quantities of open-type and outdoor gear. The plant ranges in age from a few months to 30 years or more, and much of the switchgear was suspect in respect of its fault capacity. To bring the investigation within the scope of the paper, all gear below 6 kV and all kiosk and pole-mounting-type substations, or substations supplying a single consumer of less than 2 000 kVA capacity, were excluded. A serious fire was defined as one which materially involves more than the originally faulty switchgear panel or transformer, or material structural damage. During the 18-year period the investigation showed 8 fires for approximately 2 264 substation-years of operation, or an average expectation of fire in any substation of 1 in 283 years. If transformer fires are excluded the latter figure becomes 377 years. Finally, in order to be more conservative, these figures were reduced by arbitrarily including only such of the substations as could be called "focal centres"; this gave an average expectation of fire per substation of 1 in 112 years, or 1 in 150 years if transformer fires are excluded.

Leaving this general point, Mr. Forrest suggests that there is safety in an indoor open-type arrangement in which the circuit breaker top-plate is set in a floor above an open chamber in which the circuit-breaker tank is suspended. Clearly any advantage here would be lost if top-plate or insulator failure occurred—on past experience a common result of a failure to clear a fault. The arrangement shown in Fig. 4 of the paper is designed to overcome this weakness.

This speaker also states that open-type connections should be covered with mica wrap. Unless very well done, the proposed mica wrapping is a very doubtful expedient and likely to produce a false sense of security and material risk to life. Further, if this were a sound solution it would seem worth while to "go the whole hog"—to reduce spacing, and add a metal covering to the mica wrap, thus arriving at phase isolation and metalclad switchgear. It is probably a sufficient commentary to note that the designers of metalclad switchgear have not attempted to employ mica in this manner.

Several commentators suggest that the recommendation contained in the paper that extraneous combustible matter should not be stored in switchgear chambers, is highly inconsistent with the readiness in the paper to accept oil in switchgear. This is surely an incorrect argument. In engineering practice no materials or arrangements possess all the virtues. Invariably several desirable qualities are associated with one or more undesirable qualities. It is the day-to-day task of the designer to draw the balance amongst these, and to decide when a given bad feature is outweighed by other desirable features. So with oil and compound used in switchgear: the valuable characteristics of these materials outweigh the single bad feature of inflammability. There can, however, be no argument for storing in a switch-chamber unnecessary inflammable material which could just as easily be stored elsewhere.

Concluding these general comments, it is clear from a study of the discussions that I have failed to convey a correct impression of my real attitude to the matter of oil-less circuit breakers. The contribution of Mr. Nelson in particular points to this. It therefore seems worth while to recapitulate my views on the subject.

There can be no question that if fire risk were the only or the all-important question in the design of switchgear then the elimination of combustible insulation would be a complete solution of this problem. This is, however, very far from being the fact. The oil risk is a rare hazard amenable to simple precautions in commercial practice. Given the application of these precautions, the oil risk falls to a contingency of the second order only, and need not be allowed to restrict decisions on more important aspects of the switchgear problem. Recent oil-fire experiences have all had reference to situations in which this particular risk had been imperfectly understood and the simple precautions had been neglected. These experiences have resulted in a totally unbalanced reaction and a quite improper emphasis on this single aspect of the much wider problem of switchgear design and arrangement. That I am a strong advocate of metalclad switchgear I will readily concede, though by no means agreeing that the development of this type is complete. It is because of my strong conviction of the general merits of this type that I wish to rebut strongly undue emphasis of a minor and reasonably controllable aspect of its application.

It is proper to add that where commercial considerations justify the use of open-type outdoor switchgear, as

in most 132-kV work in this country, naturally there can be no special objection to the use of air-blast switches as an alternative to oil switches.

Busbar-Zone Protection

The attitude to this problem expressed in the paper also appears to have been incompletely understood. Sustained arcing in the presence of inflammable material and air must produce fire and must aggravate it. Hence there can be no disagreement on the need to cut off supply to a faulty point as quickly as possible.

Further, if it is desired to give some measure of guarantee in this way against fire occurring, very high speed of interruption of supply is the essence of the problem. With several thousand amperes of fault current flowing in an arc, time-intervals of a second are probably quite adequate in many cases to produce fire. Hence manual interruption of supplies to a faulty busbar must be too slow to give any particular guarantee of prevention of fire. The purpose here can only be in the main to prevent the subsequent continuous aggravation of the conditions and to facilitate attack. To give any guarantee on these lines against the occurrence of fire, automatic protection becomes essential, and such protection must be rapid.

In passing, it may be noted that graded earth-leakage schemes are unlikely to give satisfactory results, because of the long time of clearance amongst other reasons.

Finally, in no sense can busbar-zone protection offer any absolute guarantee against fire. In particular, the explosive failure of a circuit breaker or insulated part may produce practically instantaneous fire, irrespective of protective devices.

Briefly, then, the principle can be accepted that it is desirable to cut off supplies as quickly as possible after a fire and that it is preferable that this should be effected by rapid protective arrangements; but it must not be assumed that any absolute guarantee against fire is secured in this way or that other precautions should be neglected.

It remains to consider the practical application of the principle, and here much misunderstanding exists. Several speakers refer to the existence of sound busbar protective schemes in various parts of the world, and I suggest that it is unlikely that many of these will bear close scrutiny. It is difficult to summarize all the requirements of a busbar protective scheme without recourse to numerous practical examples in detail, but on page 725 I indicate some of the requirements. To the best of my knowledge only one scheme exists which reasonably meets all the requirements, and two others which approach them. All of these are of very recent development. They are all fairly complex and expensive to apply, particularly to existing switchgear, and all of them cover earth faults only.

Mr. Brookman's written contribution on this subject is very valuable, and his tables are of particular interest. One can feel considerable sympathy with Mr. Brookman's attitude of mind to the busbar protection problem *in the conditions with which he has to deal*, but herein lies the real explanation of the caution expressed in the paper on the subject. He discusses a system of 14 substations on which 68 busbar faults occurred in 14 years. One would be inclined to suggest that attention was required here not to busbar protection but to prime design, to reduce faults, but since the total load capacity of the substations is probably not more than 25 000 kVA they do not really come within the scope of the paper. For the purpose of argument, however, it may be conceded at once that to a major system having such a large number of busbar faults the application of busbar protection is imperative, and incorrect operation of the order of 1 in 7 operations is not unacceptable in these conditions. For true major substations in this country, however, such a record of faults would be considered intolerable; and, taking the other end of the scale, even if the expectation of faults in a major station in this country were as high as, say, 1 in 20 years, a system of busbar protection which introduced 6 incorrect operations in this period would be considered equally intolerable. Hence the emphasis on caution contained in the paper, and the suggestion that dual check relays are essential. Mr. Brookman's own explanation of the cause of the incorrect trips on his system is an excellent indication of the risks attendant on the use of incomplete busbar-zone protective schemes.

Mr. Howarth makes reference to a particular experience of busbar fault and suggests that an earth alarm bell should have been provided. I believe I am acquainted with the case cited, and I would point out that earth alarms were fitted on this system but the faults produced peculiar conditions which negatived their value. Only true busbar protection or fault indication could have dealt with the situation. It is important to note here that busbar-fault *indication* calls for the same manual action as would be effected by busbar-fault *protective* equipment. Hence the use of fault indication only, as distinct from automatic protection, does not permit relaxation of the requirements in respect of the gear fitted.

Incidentally, Mr. Howarth refers in this case to restoration of supply *after " a matter of days."* Surely he means restoration of *duplicate* supplies—a most important difference. In the case cited the faults resulted in quite short-time interruption to supplies, although it was some days before normal duplicate supplies were entirely restored.

Mr. Swann refers to possible legal interest in this subject. Assuming that he is not blindly insisting on the mere letter of the law, it is difficult to conceive on what ground of accident experience any serious legal interest in the subject could be based. That fires and explosions have occurred is true, that any material number of serious personal injuries have occurred in major substations due to these is very doubtful, that any such would have been precluded by busbar-zone protection is more than doubtful.

Methods of Fire-Fighting

Many speakers make quite positive statements on this subject. I myself, however, was most careful to express a present opinion only, without too great emphasis. My views were based on a considerable direct experience of full-scale experimental work undertaken both by manufacturers and by undertakings, coupled with personal examination of the results of a number of serious fires.

The discussion has not produced anything to cause me to change my views, but I would suggest that actual large-scale electrical fires are so rare that no single practical example has occurred in which any of the types of fire-fighting device discussed have been tried out in real operating conditions. Pending experience of this type, absolute choice of any type is unjustified and it seems futile to carry the argument further.

Certain speakers refer to the use of CO_2 in fire-fighting, asserting that it is only suitable for fighting fires at ground level and that windows might release the gas. CO_2 is essentially an arrangement for the quick smothering of a fire, and thereby the prevention of serious thermal effects on a structure. Hence wired glass, which is recommended in the paper, should provide adequate enclosure, as, whilst this type of glass may crack largely, it retains its form subject to the fire not being maintained for too long a period. The correct disposition of the discharge nozzles is anywhere but at floor level, and they should be arranged partly for direct discharge in the vicinity of the gear to be protected and partly for general discharge from a moderately high level. Further, it is essential to allow a very large volume in each charge for leakage and to have a second charge in reserve.

It should be remembered also that the discharge is under considerable pressure, that in switchgear examples the initial fire is usually contributed to by the failure of a single circuit-breaker or part, and that the continued large-dimension fire is a subsequent development consequent on the failure to deal rapidly with the initial development—hence the need for automatic fire control in unattended stations. CO_2 is, of course, preferred because of its freedom from damage to insulation, but even with other forms of local fire-quenching device it is frequently not possible to allow for other than short-time attack—hence the need for a second line of defence, suitably co-ordinated in advance, in the general fire system of a power station and in the public fire service. It may again be stressed here that the ultimate and all-important fire precaution is the physical separation of duplicates in chambers designed so that fire cannot be transmitted from one to another.

It may be conceded to Mr. Headland that there is some room for personal opinion in respect of the fire protection of alternators where these are of the open-circuit type, as is usual with large water-wheel machines. Opinions, however, can only properly be based on experience, and from my experience of alternator faults in a large number of generating stations of which I have direct information, mainly of the steam-turbine-driven type with closed-air circulation, I can quote no single instance in which the burning of combustible material following a fault was very material or likely to have been decreased to any material extent by CO_2 or other provision. In the plant in mind the protective system was arranged to cut off the air supply in nearly all cases.

I am in general agreement with the bulk of Mr. Fordham Cooper's remarks on fire fighting, but I doubt whether special arrangements are necessary to meet the case of oil continuing to burn inside a transformer. Usually the external means of attack appear satisfactory, the internal fire being quenched by the products of combustion and by the difficulty of air access, both natural and due to the external blanketing of the agents in use

Several references have been made to the toxic qualities of carbon tetrachloride and methyl bromide. I can only say that, whilst toxic possibilities definitely exist, my experience does not indicate that they are a serious menace in practice. I would not, however, recommend their use in a confined space unless human access was denied.

It should be made clear that CO_2 is not poisonous, nor even urgently dangerous if discharged before men get clear. Provided they get away as quickly as possible no serious results are likely.

I am unable to agree that, except in particular instances, there is any need for special locks to prevent the CO_2 apparatus being discharged while men are working. Notices and audible alarms should be adequate.

Mr. McMahon refers to the danger of the production of boiling action by pressure water spray. I have witnessed several experiments with tanks of oil, including old transformer tanks, in which the oil was first artificially boiled, and I am satisfied that if the spray pipes are correctly disposed any boiling-over action will merely prove a minor incident in a successful extinction.

Protection of Cable Terminations

Many useful remarks have been made on this subject. The method indicated in Fig. 2 of the paper was not intended to be other than a single example of many possibilities.

Mesh-Type Substations

These, whilst offering fairly good busbar facilities, suffer from several disadvantages. Chief amongst these is the risk of a serious disorganization of supplies should a failure occur on one circuit whilst another is being examined.

Subdivision of Switchgear Chambers

No one will quarrel with Mr. Forrest's wish to have completely separate and widely-separated switch-houses for each section of switchgear. This is naturally the ideal physical separation. If, however, he adheres to his preference for open-type switchgear, it may be remarked that he is likely to find some difficulty in arranging the centres of his independent widely-separated switch-houses so as to coincide with the turbo-alternator centre lines.

Mr. Coates introduces in his Fig. D an additional longitudinal subdivision of the diagrammatic arrangement shown in Fig. 1 (*f*) of the paper. I am unable to appreciate that this gives other than a secondary improvement to the arrangement, since a fire in any one of the chambers must be assumed to damage the insulation of the horizontal cross-connections which pass through the additional walls and hence to render the busbars unusable in the parallel chamber. Hence this can be considered to be a provision only for reducing the consequential damage in a fire. Obviously this line can be followed until we achieve metalclad cubicle gear. The first division of the switchgear into two truly duplicate

parts in separate chambers is the prime and overriding requirement in all fire, explosion, etc., precautions. Add to this reasonable fire-fighting arrangements, and in metalclad practice no further subdivision is worth while. Fires are so infrequent and sound metalclad gear possesses such an extraordinary degree of resistance to internal fire attack, as shown by actual experience, that further restrictions in the layout or increased expenditure need not be incurred, although none will object to these where the general design makes the provision easy.

Precisely similar arguments apply to Mr. Davies's Fig. E. I have no objection to the additional subdivision indicated, as it is inexpensive and easy to obtain. Were the opposite the fact, however, I should not be in the least disturbed at its omission. Commercial experience has not shown any justification for material expenditure on these lines.

Mr. Longman's remarks regarding separation of duplicate busbars on metalclad switchgear are open to precisely the same objection. Given a single circuit-breaker, connections from both busbars must pass to the common oil-switch chamber and hence be jointly vulnerable.

Regarding Mr. Davies's remarks on star reactance schemes, there is no fundamental difference in principle between ring-busbar and star-busbar schemes. The latter are somewhat easier in physical arrangement. On the other hand, no one has yet faced squarely the accumulation of fault capacity on the star busbar itself.

Insulation Testing

I agree that the portable Schering bridge offers a sound method of testing insulation, but I hesitate to agree that it is necessary to make a range of tests at various voltages, because of the doubtful practicability of this due to the time involved. I am of the opinion that for insulation of the condenser-bushing type there is inadequate knowledge at present to permit rejection, except when power-factor and watts-loss tests give figures outside rather wide limits. For the time being, the only true check is by the comparison of results obtained on a number of insulators of the same type, plus the comparison of the results obtained in successive periodic tests on each individual insulator, which shows up the rate of deterioration. No doubt in the course of time the accumulated experience obtained in this way will result in a better understanding and a narrowing of the rejection limits, and more particularly in a general improvement in the design and manufacture of the insulation itself.

Sectioning of Existing Substations

Several speakers refer to the difficulties of dealing with existing substations in which the precautions are incomplete or non-existent. I am fully appreciative of the difficulties, having dealt with some hundreds of examples. Unfortunately, without citing examples at great length, it is impossible to give an adequate answer on this subject, particularly since the importance of the substation and the risks entailed due to the position, etc., must determine the extent of the modifications. However, the most usual arrangements are on these lines:—

(*a*) Remove one or two switches to enable a section wall to be built.

(*b*) If the extension space directly available does not permit of the re-installation of the displaced switches and any additional coupling switches which may be necessary, investigate the possibility of installing all the coupling switchgear in an adjacent chamber or one near by. The removal of these usually provides the necessary space for the displaced feeder switches. The coupling switchgear must then, of course, be cabled back to the two separate busbars now established.

(*c*) If (*a*) and (*b*) are not possible, consider whether minor system rearrangement is possible to achieve similar results.

(*d*) Assuming that (*a*), (*b*), and (*c*) are not possible, attention must then be paid to emphasizing fire precautions, automatic fire equipment, etc., and preferably busbar protection. It should, however, not be overlooked that in the occasional example of major importance complete structural rearrangement may be justified, and even switchgear replacement. Where the existing switchgear is of the open type, replacement by metalclad gear will always offer a solution. Such replacement may be in part only if cost is the governing factor.

General

I agree with Mr. Kidd on the commercial limits he suggests for switchgear fault capacity at various voltages, provided these apply to general system switchgear only and not to major generating stations. For the main switchgear at large generating stations, and in fact for what may be called the pure transmission or bulk-supply network, larger sizes are most frequently essential to secure reasonably free busbar facilities. The designer's problem is to meet both these requirements simultaneously. This forms part of a much larger subject which it would not be proper to discuss here.

Mr. Kidd and Mr. Howard refer to the use of cable boxes on transformers. Wherever there are special reasons for their use in this manner I have no hesitation in applying them. There is some doubt, however, whether they contribute more to the fire risk than separate sealing-ends, and therefore there is room for personal opinion in respect of their general application. A number of cheap designs of cable box are on the market with inadequate clearances and filling arrangements, and the use of ordinary black compound for filling is a common weakness. The difficulty of removing a transformer fitted with cable boxes is not serious. This is a rare requirement, but can be dealt with quite reasonably when the layout is being settled.

Several speakers discuss the steam-turbine oil-fire risk. While this matter does not come within the scope of the paper, nevertheless I would say that in my view no completely satisfactory method of dealing with it has yet been evolved; I am of the opinion that a rearrangement of the oiling system is the first essential.

My attitude to the conflict between air-raid requirements and the normal provision of windows for internal-explosion relief is to fit the latter in the ordinary way and to make provision for hanging steel shutters over the windows in the event of war, when the internal-explosion risk, which is remote, can reasonably be

accepted. Some argument may develop about the thickness of the steel shutters, and in this connection it should be remembered that metalclad switchgear is to a considerable degree splinterproof. Alternatively, the windows may be bricked up when war is declared, but objection has been made to this on the score of speed.

Mr. Ellis's rewording of the remarks in the paper on inter-turn faults on transformers is fair. Quite a number of barrier walls have been installed in outdoor sub-stations recently. I agree, however, that wide spacing with a pebble surround is a reasonable alternative to barriers. Whilst I agree with Mr. Ellis that burst transformer tanks are very rare, I have little faith in explosion diaphragms and I know several cases of damaged tanks and joints in which the explosion diaphragm has remained intact.

Mr. Davies comments on my accepting lead on cable connections whilst condemning aluminium for switchgear. He may be reminded that precautions are suggested in the paper against the weakness of lead, and that the aluminium which is condemned either surrounds busbars or encloses oil or compound. The condemnation is the result of direct practical comparison of the effects of fire on aluminium and cast iron or steel. The gunmetal alternative at least achieves a halfway house between aluminium and cast iron in respect of melting point, and in any case it is not certain that melting point is the only criterion in this matter.

Regarding Mr. Flurscheim's statement as to the good record of cross-jet pots, there can be no important difference between these and several other similar types of arc-control device of which I have seen explosive failures on test. If the strength of the pot is inadequate, explosive failure will result. Of the many explosions of switchgear which I have seen, the worst was of this type.

I agree with several speakers that where large quantities of oil are to be dealt with provision should be made for the drainage of this from pebble sumps. The ideal type of fill for these sumps would be marbles, but the most practical is undoubtedly screened pebbles.

Mr. Innes makes reference to the recommendation by a London fire officer that high-resistance gloves and footwear should be part of the equipment of all fire brigades. I have always felt that this type of protection is more illusory than practical.

Notes on Busbar-Zone Protection

In conclusion, I propose to give some details of the requirements to be met by busbar protective schemes, to which brief reference was made on page 722.

Theoretical requirements.

The protective equipment must be fully discriminative, i.e. must operate to disconnect the faulty section of busbars only. (In substations of lesser importance a complete shutdown of all busbar sections may be permissible on the basis of the rare occurrence of the contingency.) The protection provided should cover both phase and earth faults. (In practice the additional provision for phase faults increases the complexity so much that this provision is disregarded.) The sensitivity of the protection must be adequate to ensure tripping on internal faults under minimum in-feed conditions. The protection must be completely stable on all faults outside the busbar-protected zone, whether this be of the interphase or the earth-fault type.

In order to reduce the risk of fire, the isolation of the faulty busbar should be as quick as possible, and for this reason it is desirable to arrange a scheme so that any section or coupler switches are tripped at the same time as the other switches connected to the busbar. This is much more difficult to arrange than sequential tripping, and in stations of comparatively minor importance sequential tripping might be tolerated provided that the protection on the incoming feeders was not of the distance, rapid overload, or similar type. If the protection is of this type, it is essential to arrange for simultaneous tripping of all switches connected to the faulty busbar, as otherwise the protective gear at the remote end of each feeder with such protection will clear first.

In order to avoid cock-up voltages on the system and the risk of faults on other phases, all circuits connected to the faulty busbar, whether they can feed fault current or not, must be tripped.

Where bypass isolators are provided on the line circuit-breakers, automatic means must be provided for rendering the busbar protection inoperative on any section to which a feeder is connected through its bypass isolator.

Schemes of Busbar-Zone Protection

General principles.

The various schemes of busbar-zone protection so far produced may be classified roughly under the following headings:—

(1) Frame-leakage protection, necessitating the insulation of the switchgear frame from earth and the provision of one or more current transformers slipped over the frame earthing connection.

(2) Some form of Merz–Price protection whereby the total current entering a section of busbars is compared with the total current leaving a section of busbars. If the total current entering the busbars exceeds the total current leaving the busbars, there is a busbar fault.

(3) Directional protection on the interlock principle. This form works on the principle that whenever there is a busbar fault any circuit which is capable of feeding fault current must feed power towards the faulty busbar and cannot possibly feed it away. If the direction of power flow on any circuit is away from the busbar in the event of a fault, the busbar protective equipment is locked out and no switch is tripped.

All the schemes which I have so far encountered employ one or more of the above principles.

Disadvantages.

The following are the principal disadvantages of each of these forms of protection.

Frame leakage.—(*a*) Great care has to be taken in insulating the switchgear frame from earth, although the actual standard of insulation is not high. The provision of adequate insulation is much more difficult on certain types of gear than on others, and each case has to be considered on its merits. Even when perfect insulation has to be provided in the initial installation

the inadvertent connection of the gear to some external earthed metal may render the busbar protection inoperative. The adequate maintenance of the insulation is difficult. The insertion of a sufficient number of insulated points in certain types of gear in order to split up the fault zones may be extremely difficult from a mechanical-design point of view. In other words, in this form of protection it may be extremely difficult to obtain full discriminative protection.

(*b*) Inadvertent operation may occur due to, say, a frayed lead connected to the station auxiliary supply coming into contact with the switchgear frame (Mr. Brookman quotes one experience of this sort).

Merz–Price.—(*a*) With this form of protection full discrimination with duplicate busbar gear can fairly easily be obtained if auxiliary switches are included in the current-transformer secondary circuits. General past experience, however, indicates the unwisdom of this due to the possibility of bad contact arising in the auxiliary switches and causing instability. There has recently been developed, however, a scheme where the auxiliary switches are continuously checked by a small external supply which is insufficient to operate the busbar protective relays; but even this may fail under certain conditions, and it cannot, therefore, be regarded as completely safe. For all important stations, therefore, it is regarded as essential that discrimination should be obtained by the insertion of auxiliary switches in the d.c. circuits. This can be done, but it is very much more difficult, as an examination of the problem will quickly disclose.

(*b*) In large stations a large number of current transformers have to be connected in parallel, and great care has to be taken to ensure that any group of current transformers are properly balanced so as to ensure stability on external faults. This also involves care in running multi-core cables, since the burdens on the various current transformers must be kept approximately equal. In general this means that all multi-core cables must be brought back separately from their own sets of current transformers to the busbar protective relay panel before they are commoned.

(*c*) In order to reduce the burdens from the current transformers to a reasonable amount, it is often necessary to employ multi-core cables of very large section.

(*d*) The open-circuiting of a current-transformer secondary will give rise to trouble on through faults. The very large number of current transformers connected together must be remembered in this connection. The trouble can be dealt with to a certain extent by sensitive alarm facilities and routine testing, and in any case is less likely to occur when auxiliary switches are *not* included in the current-transformer secondary circuits.

Directional protection.—There is only one important objection to this scheme and that is that an open-circuited current-transformer secondary may give rise to an incorrect direction of operation.

Precautions.

For important stations it is not considered that any one of the above schemes by itself is safe, and for such stations there should be two independent lines of defence, either one of which can operate incorrectly on external faults without incorrect operation of the busbar protective equipment as a whole being obtained. Thus a combination of, say, frame-leakage and Merz–Price, Merz–Price and directional interlock, or directional interlock and frame-leakage, may be employed.

The inadvertent operation of any single relay, whether by hand, mechanical vibration, mechanical defect, or electrical means, should not be capable of operating the busbar protection as a whole. (This point is partly covered by the previous paragraph.)

It is desirable to provide a sensitive alarm relay with either Merz–Price or directional interlock protection, so that in the event of a current transformer becoming open-circuited the alarm will sound on load current and avoid busbar shutdowns later on feeder faults.

It is very desirable to provide adequate links and testing facilities generally to enable regular routine tests to be easily carried out on the busbar protective equipment.

For important installations it seems desirable that the busbar protective relays should be mounted on a separate panel and that entirely separate multi-core cables should be used for busbar protective purposes.

For important stations it is highly desirable to make use of separate current transformers for busbar protection. If instrument current transformers are used, ammeter switches must be omitted.

It is highly desirable to provide separate trip coils for busbar protection, since otherwise it is necessary to provide either multi-contact tripping relays or separate individual tripping relays. The second alternative requires a large number of additional relays, and the first alternative suffers from the disadvantage that, if a multi-contact tripping relay is inadvertently left in the operated position, the tripping of any single circuit-breaker either by hand or by local protective gear will trip all the switches connected to the busbar.

If one commences to design a scheme of busbar protection taking the above requirements into account, it will soon be found that a further number of rather unexpected difficulties have to be met. It is not possible to generalize on these, since each case has to be considered on its merits, but much care and thought must be exercised.

THE EFFECT OF CHANGE OF TEMPERATURE ON THE STRENGTH OF PERMANENT MAGNETS, WITH SPECIAL REFERENCE TO MODERN MAGNET STEELS*

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SUMMARY

A survey is made of the literature and it is found that a magnet can be put into the steady condition, as regards magnetic strength, by mechanical shocks or by cyclic heating, and then it has a definite strength at each temperature, the connection between the two generally giving rise to a negative coefficient. The majority of the experimenters have assumed a linear relationship and have determined the strength/temperature coefficient from measurements at two temperatures only. A summary of published work shows that the coefficient depends upon the linear dimensions of the magnet and can be reduced by increase of the length/breadth ratio, by increase of the degree of drawing, by heat treatment, or, in the case of carbon steels, by increase of the carbon content.

In the present paper a description is given of a rotating search-coil and ballistic-galvanometer arrangement for testing cobalt steel, aluminium-nickel, and aluminium-nickel-cobalt alloy magnets over the temperature range − 60° C. to 100° C. An electrically heated oil bath was used for the range 20° C. to 100° C., whilst solid carbon dioxide dissolved in acetone was employed for the range 20° C. to − 60° C. When the magnets had attained the reversible state it was found that the magnetic strength H_τ could be connected with the temperature τ(°C.) by an equation of the type

$$H_\tau = H_0(1 + a\tau + b\tau^2)$$

where a and b were negative constants and were determined for each magnet. The total permanent loss of strength up to the attainment of the steady state was also measured. It was found that, in the case of the cobalt-steel magnets, the coefficient a was reduced by increase of the cobalt content; the total loss was similarly affected, but not to such a marked extent. In the case of 15 % Co steels and the Al–Ni and Al–Ni–Co alloys, a and the loss were affected by the temperature at which magnetization was performed. The other cobalt magnets were magnetized at ordinary temperatures.

INTRODUCTION

The strength of a permanent magnet changes with alteration of its temperature and, in general, the strength diminishes when the temperature is raised and increases if it is lowered. The constancy of the strength of a magnet is of paramount importance in the case of highly accurate instruments or electricity meters. Many of the instruments employed on aircraft are electrical in character and contain permanent magnets; so that, in view of the developments that have been made in high-altitude flying, where very low temperatures are encountered, it has become necessary to know something of the behaviour of magnets at low temperatures. A great amount of research has been done already in the determination of the coefficient of the change of strength of a magnet with temperature, although most of the experiments have been confined to measurements of the strength of the magnet at atmospheric and steam temperatures, and the assumption of a linear connection between strength and temperature. One or two of the workers in the subject have placed on record the fact that the strength/temperature relationship is not linear, but can be expressed by an equation of the type

$$H_\tau = H_0(1 + a\tau + b\tau^2)$$

where H_τ is the strength at a temperature τ° C., H_0 that at 0° C., and a and b are constants and are usually negative.

The published work dealing with the subject shows that:—

(i) In general, a magnet experiences a reduction of magnetic strength when its temperature is raised. When the temperature is dropped again to its initial value, the strength increases but does not reach quite to the starting value. This loss occurs to a decreasing extent during the first few cycles of temperature, after which the magnet reaches a reversible condition in which it has a definite strength for each temperature. When a magnet has reached this steady state, its strength is usually reduced by an increase in temperature unless the metal has been specially prepared.†

(ii) If the temperature of a magnet is taken below its magnetization value, there is an increase of magnetic strength, but when the temperature is raised again to the initial value there is a permanent loss of strength, as in (i). Once again, several temperature cycles are necessary before the magnet reaches the reversible condition, and then its strength is usually raised by a reduction of temperature.‡

(iii) A magnet which has attained the reversible condition by a series of heating cycles between two limits of temperature is only in the reversible state for those temperature limits, and not for any others.§

(iv) There is a definite connection between the strength of a magnet in the reversible condition and its temperature. Many writers have assumed this relationship to be linear‖ and have calculated the temperature coefficient

* This paper is a summary of a dissertation approved for the degree of Master of Science (Engineering) in the University of London.

The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Bibliography, (1), (2), (3), (4), (5), (9), (11), (13), (14), (15), (24), (42).
‡ *Ibid.*, (10), (22), (23), (26).
§ *Ibid.*, (36).
‖ See in particular, Bibliography, (4), (9), (11).

from measurements at two temperatures only. A few experimenters have stated that the connection is of the second order* and that the reduction in magnetic strength per degree rise of temperature increases with rise of temperature.

(v) The temperature coefficient of the linear relationship is generally negative and has a value of the order of 0·00010 to 0·00050: 1 per degree Centigrade.

(vi) The coefficient can be decreased by an increase of the ratio of the length to the breadth of a bar magnet,† or by a corresponding change in the shape of other forms. A short gap between the poles and a large pole-face area (or area of cross-section of pole-gap) are desirable features in the case of horseshoe magnets.‡

(vii) The temperature coefficient falls linearly with increase of the strength of a field acting in opposition to the intensity of magnetization.§

(viii) It has been found by experiment, and it can be deduced from (vii), that the coefficient is dependent upon the intensity of the field due to the magnet.‖ The exact relationship has not been determined experimentally.

(ix) The coefficient obtained with an infinite value of the length/breadth ratio, or with the field mentioned in (vii) equal and opposite to the intensity of magnetization, is characteristic of the material composing the magnet.¶

(x) Increase of the carbon content up to a certain limit produces a reduction of the temperature coefficient of carbon and chromium steels, since, other things being equal, increase of carbon content tends to produce increase of coercive force, which is equivalent to the result recorded in (vi).**

(xi) In one series of tests it was found that the chromium content appeared to have no effect upon the temperature coefficient.††

(xii) The temperature coefficient can be reduced by suitable heat treatment.‡‡

(xiii) In the case of magnetized piano wires of constant length/breadth ratio, it was found that the degree of cold drawing affected the temperature coefficient, the negative temperature coefficient approaching zero as the drawing was increased.§§

(xiv) The permanent loss of magnetic strength which occurs during the initial temperature cycles of an aged magnet (one subjected to ageing before magnetization, but not treated afterwards) can be reduced by increase of the length/breadth ratio.‖‖

(xv) In the case of carbon-chromium steels, the loss mentioned in (xiv) can be reduced by increase of the chromium content, and, with steels of low chromium content only, by increase of the carbon content.¶¶

A search through the literature of the subject appeared to show that there were no systematic measurements at temperatures below atmospheric and that the second coefficient of the strength/temperature relationship had not been determined by any of the workers on the subject. As far as the author is aware, no results have been published of the temperature coefficients of magnets composed of modern high-coercive-force alloys, such as cobalt-steel, aluminium-nickel, and aluminium-nickel-cobalt. The remainder of the paper is devoted to the study of these materials over the temperature range −60° C. to 100° C.

MEASUREMENT OF POLE STRENGTH OF PERMANENT MAGNET

A magnetometer arrangement was tried, but was found to be too sensitive to stray fields. The Hull* magnetron method was attempted, but the anode current did not fall with sufficient abruptness at the critical anode potential to give a precise measurement of the strength of the magnetic field; thus the arrangement was unsuitable for recording small changes of strength.

It was finally decided to employ a rotating search-coil to measure the strength of the field between the poles of horseshoe magnets, and the apparatus shown in Fig. 1 was constructed, two sets of equipment being made to accelerate the work. The metal portions of the apparatus were of brass. The search coil, S, was of the bakelized formerless type, and contained 100 turns, each of which was a square of approximately 1·5 cm. side, two sides of which were horizontal, whilst the plane of the coil was vertical. Movement of the ring, A, caused the slider, K, to move along the square thread, J, of a steep screw at one end of the spindle, M, and thus the search coil was rotated through exactly 180°. The coil was rotated through an equal angle in the opposite direction when the ring was moved back to its initial position. The bronze bolts, B, held the search-coil tube, D, to the brass tank, E, and also kept the magnet in position with the search coil midway between the poles. Each set of the apparatus could be connected with a ballistic galvanometer via a mercury switch (see Fig. 2 for circuits). The moving-coil galvanometer employed had an internal resistance of 1 000 ohms, and, with the strong magnets tested, it was necessary to put 500 ohms in series with the instrument to reduce the deflections to reasonable values. With this arrangement the galvanometer was exactly dead-beat, and it was found that, provided the movement was reasonably rapid, the speed of the movement of the sliding ring had no effect upon the deflection. The conventional lamp, mirror, and scale arrangement was employed, the scale stand was screwed to the laboratory bench, and the galvanometer was suspended from the wall of the building in an anti-vibration cradle. The scale distance was 163·1 cm., and, when the temperature of the test magnet was maintained constant, the values of consecutive pairs of deflections repeated to within 0·1 mm., which, since the total deflection was generally of the order of 20 cm., gave a repeatability of 1 in 2 000, or 0·05 % of the field strength. The mean of the two deflections obtained when the coil was rotated in each direction was recorded.

It is unnecessary to know the actual value of the flux density in work of this type, and it is quite sufficient to obtain readings of the percentage change of the field strength as represented by the change of the galvanometer deflection. It was, however, very necessary that the galvanometer calibration should be checked frequently, and the arrangement shown in Fig. 2 was employed. The calibration curve was linear, and re-

* See in particular, Bibliography, (1), (13), (15), (31).
† See Bibliography, (4), (9), (11), (14), (16), (39).
‡ *Ibid.*, (39).
§ *Ibid.*, (40).
‖ *Ibid.*, (6), (16), (25), (39).
¶ *Ibid.*, (40).
** *Ibid.*, (37), (38).
†† *Ibid.*, (41).
‡‡ *Ibid.*, (19), (37), (38), (42).
§§ *Ibid.*, (12).
‖‖ *Ibid.*, (11).
¶¶ *Ibid.*, (41).

* See Bibliography, (48).

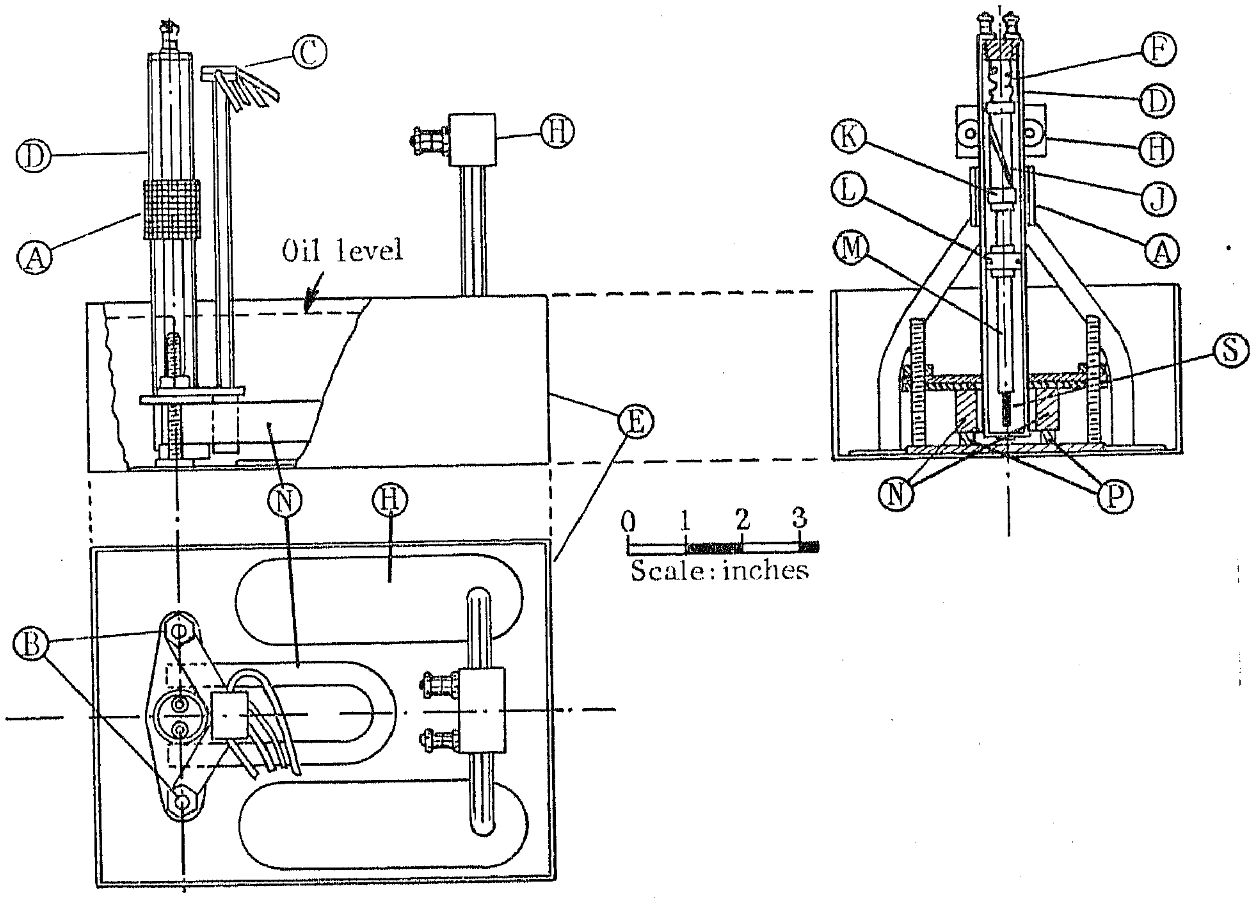

Fig. 1.—Diagram of search-coil apparatus.

E = Brass tank.
H = 300-watt a.c. heater.
N = Magnet under test.
C = Platinum thermometer.
D = Brass tube containing spindle M.
L = Spindle bearing.
J = Steep thread on M.
A = Milled ring connected with slider K, which meshes with J.
S = Search coil.
B = Clamping screws.
P = Packing.
F = Flexible leads to S.

peated satisfactorily throughout the work. A rough calculation showed that the sensitivity of the apparatus was 0·493 mm. deflection per gauss.

A platinum resistance thermometer connected with a Carey-Foster type bridge was employed to measure the temperature of the baths in which the magnets were placed. The instrument was calibrated in melting ice and at steam temperature, and was checked at the temperature of solid carbon dioxide.

The tank shown in Fig. 1 was filled with transformer oil for experiments over the temperature range 20° C. to 100° C., and with acetone for experiments over the range down to – 60° C. The oil bath was heated electrically by the flat heaters, H, for the upper temperature range, and air stirring was employed. Solid carbon dioxide was dissolved in the acetone to give the lower temperatures and, when a piece was put in, a very vigorous bubbling occurred and the bath was stirred. By putting a few pieces of carbon dioxide at a time into the bath it was possible to reduce the temperature in quite small steps. The a.c. heaters were employed to heat the acetone bath, and this also caused vigorous bubbling.

MATERIALS TESTED

3 %, 6 %, 9 %, and 35 % Co-steel horse-shoe magnets were obtained from a manufacturer and were magnetized at the works. A set of 15 % Co magnets was received in the unmagnetized condition, but had been treated up to the point of magnetization. The chemical analyses of the materials are given in Table 1, the figures being the " standard " analyses supplied by the makers. It was not thought worth while to make an exact analysis since it frequently happens that two magnets having exactly similar chemical analysis have rather different magnetic characteristics and, in addition, heat-treatments play very important parts in these matters. The cobalt

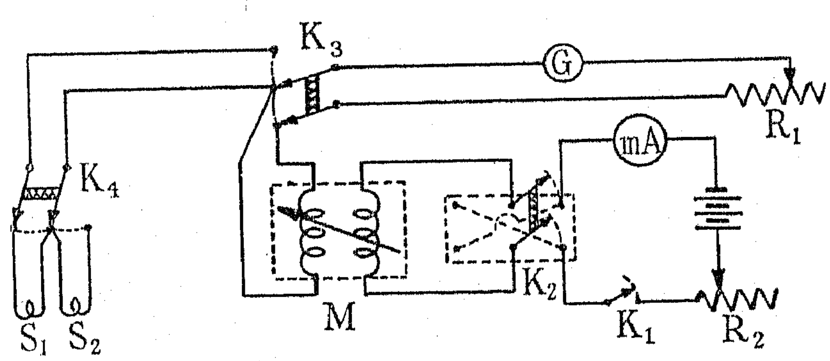

Fig. 2.—Circuit arrangements for measurement of flux density and calibration of galvanometer.

S_1 and S_2 = Search coils.
G = Galvanometer.
R_1 = Resistance box.
R_2 = Rheostat.
M = Mutual inductance (variable).
mA = D.C. milliammeter.
K_2 = Double-pole double-throw switch.
K_3 and K_4 = Mercury switches.

steels were all given the well-known " triple " heat treatment, but variations were made in the third portion of the treatment. The 35 % Co steel, after the first two treatments, was quenched in oil from 920° to 940° C., the pieces being rapidly moved about in the oil bath to accelerate the cooling. The magnets of the other cobalt contents were heated to 1 000° C. and immediately removed from the furnace and placed in a low-pressure air blast until the pieces reached 300° C.; the pieces were then quenched in oil.

Table 1

Details of Materials and Results of Tests on Cobalt-Steel Permanent Magnets

Magnet No.	Chemical composition (per cent) Co	Cr	C	Si	Mn	Wo	Mo	Magnetizn. temperature	Time from magn. to 1st cycle	Maximum flux density on C.L.*	Experimental history (h = hot cycle, c = cold cycle)	Percentage loss of magnetic strength during cycle number 1	2	3	4	5	Total permanent loss	Temperature coefficients a	b
								°C.	days	gauss							per cent		
3	15·0	9·0	1·0	0·2	0·2–0·4	Nil	Nil	By makers	16	72·06	4h; 3c; 6h	0·00	0·15	0·23	0·05		0·43	$-2\cdot093 \times 10^{-4}$	$-2\cdot49 \times 10^{-7}$
4								20	293	75·49	2c; 9h	0·06					0·06	$-2\cdot069 \times 10^{-4}$	$-3\cdot90 \times 10^{-7}$
5								160	182	75·97	2c; 7h; 1c	0·30	0·00	0·00	0·02	0·01	0·33	$-2\cdot416 \times 10^{-4}$	$-8\cdot32 \times 10^{-7}$
6								106	216	75·09	8h; 3c	0·28	0·21	0·06			0·55	$-2\cdot261 \times 10^{-4}$	$-6\cdot35 \times 10^{-7}$
7								− 66	164	73·93	6h; 2c; 6h; 1c	0·00	0·00	0·00			0·00	$-2\cdot158 \times 10^{-4}$	$-2\cdot80 \times 10^{-7}$
8								− 70	150	73·00	3c; 8h; 1c; 2h; 3c	0·15	0·45	0·00	0·45	0·10	1·15	$-2\cdot158 \times 10^{-4}$	$-4\cdot74 \times 10^{-7}$
9	3·0	9·0	1·0	0·2	0·2–0·4	Nil	1·4	By makers	90	56·39	3h; 3c; 5h	0·90	0·03				0·93	$-2\cdot147 \times 10^{-4}$	$-4\cdot78 \times 10^{-7}$
10	3·0						1·4	,,	330	55·75	7h; 2c	0·40	0·28	0·05			0·73	$-2\cdot153 \times 10^{-4}$	$-6\cdot65 \times 10^{-7}$
11	6·0						Nil	,,	100	62·55	2c; 9h; 1c; 2h; 3c	0·50	0·00	0·55	0·15		1·20	$-2\cdot399 \times 10^{-4}$	$-4\cdot56 \times 10^{-7}$
12	6·0						Nil	,,	330	62·44	7h; 2c	0·35	0·23	0·15	0·08		0·81	$-2\cdot373 \times 10^{-4}$	$-4\cdot74 \times 10^{-7}$
13	9·0						Nil	,,	150	62·32	7h; 2c	0·32	0·08	0·05			0·45	$-2\cdot093 \times 10^{-4}$	$-3\cdot77 \times 10^{-7}$
14	9·0						Nil	,,	360	63·82	7h; 3c	0·35	0·15	0·12	0·10		0·72	$-1\cdot975 \times 10^{-4}$	$-5\cdot33 \times 10^{-7}$
15	35–36	5·0	0·9	0·2	0·2–0·4	5·0	Nil	,,	150	83·75	7h; 2c	0·40	0·13	0·10	0·04		0·67	$-1\cdot787 \times 10^{-4}$	$-4\cdot69 \times 10^{-7}$
16	35–36	5·0	0·9	0·2	0·2–0·4	5·0	Nil	,,	360	82·18	7h; 3c	0·55	0·20	0·15	0·06		0·96	$-1\cdot818 \times 10^{-4}$	$-5\cdot45 \times 10^{-7}$

* The maximum flux density on the centre line of the magnet, between the limbs, was measured by the field-exploration apparatus at the conclusion of the tests.

Table 2

Details of Materials and Results of Tests on Al–Ni and Al–Ni–Co Permanent Magnets*

Magnet No.	Chemical composition (per cent) Al	Ni	Cu	Co	C	Magnetizn. temperature	Time from magn. to 1st cycle	Maximum flux density on C.L.	Experimental history (h = hot cycle, c = cold cycle)	Percentage loss of magnetic strength during cycle number 1	2	3	4	5	Total permanent loss	Temperature coefficients a	b
Aluminium-Nickel alloy						°C.	days	gauss							per cent		
17	13·6	23·5	4·04	—	0·05–0·06	20	30	71·87	7h; 3c	0·43	0·14				0·57	$-3\cdot044 \times 10^{-4}$	$-2\cdot09 \times 10^{-7}$
18						− 79	43	74·00	6h; 3c	0·45	0·18	0·18	0·05		0·86	$-2\cdot607 \times 10^{-4}$	$-4\cdot32 \times 10^{-7}$
19						100	43	70·68	6h; 3c	0·20	0·06				0·26	$-2\cdot767 \times 10^{-4}$	$-3\cdot33 \times 10^{-7}$
Aluminium-Nickel-Cobalt alloy																	
20	10·0	18·0	6·00	12·0		20	35	Approx. 42	9h; 3c	6·00	0·35	0·28	0·23	0·22†	7·08	$-2\cdot464 \times 10^{-4}$	$-8\cdot71 \times 10^{-7}$
21						100	35	Approx. 42	7h; 3c	0·67	0·05				0·72	$-1\cdot749 \times 10^{-4}$	$-4\cdot90 \times 10^{-7}$

* It was impossible to give maximum flux-density values for the Al-Ni-Co-alloy magnets because of their special construction; the approximate figures given are those at the point where the search coil was fixed during the temperature cycles.

† This loss occurred during the first of the cold cycles.

Three horseshoe magnets of aluminium-nickel alloy were also obtained: one was magnetized by the manufacturers, and the other two were treated up to the point of magnetization. The treatment given to the Al-Ni alloy in the works was to heat it to 1 150° C. and then cool in air.

Two specimens of aluminium-nickel-cobalt alloy were obtained; one had been magnetized by the makers, whilst the other was delivered ready for magnetization. The alloy material had been treated by heating to

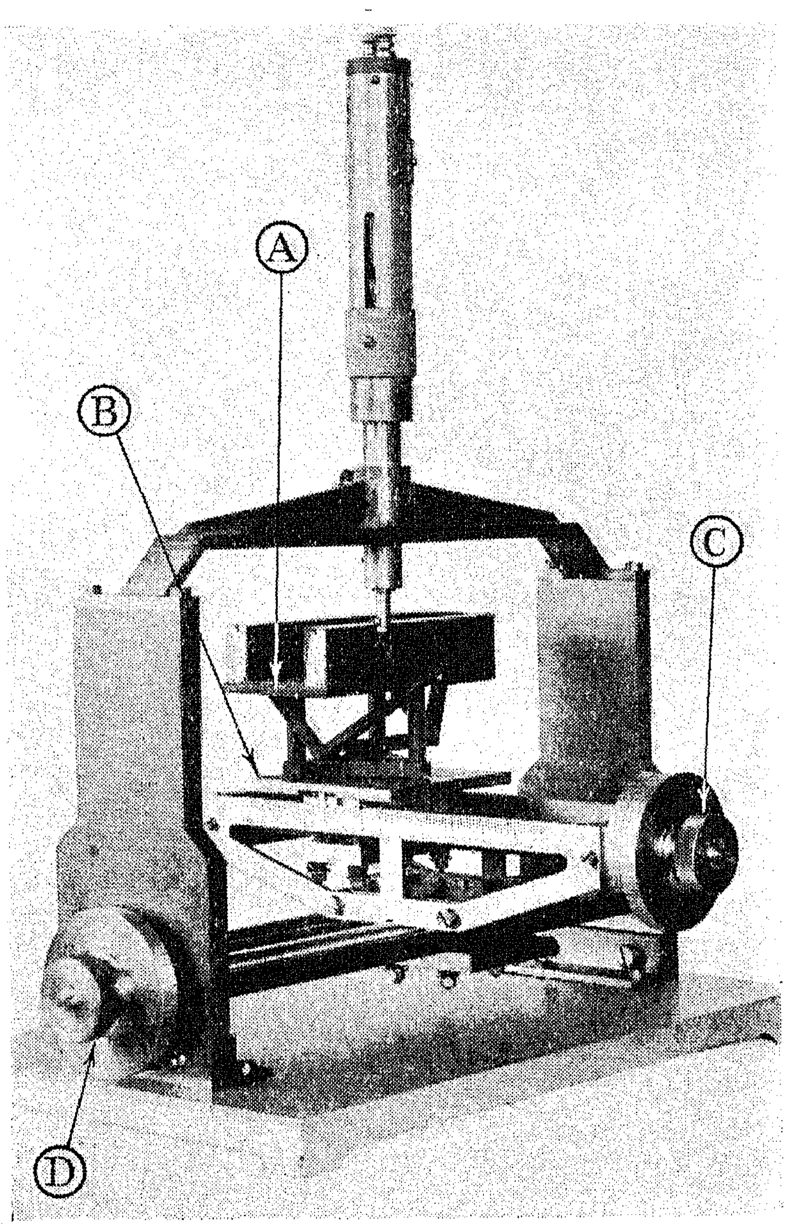

Fig. 3.—Field exploration apparatus.

1 300° C. and cooling in still air. The material cannot be cast into the horseshoe form with any degree of success, and thus magnets had to be built up. The dimensions of all of the magnets are given in Fig. 4, and it can be seen that the built-up magnets possessed a yoke portion of alloy material, whilst the limbs were made of mild steel held hard against the yoke by phosphor-bronze screws passing from one limb to the other through channels cut in the alloy piece. The chemical compositions of the Al-Ni and Al-Ni-Co alloys are given in Table 2.

It was decided to determine the effect of alteration of the temperature at which magnetization was performed upon the subsequent magnetic properties. The temperatures employed are given in Tables 1 and 2; the upper temperatures were obtained by electrically-heated baths of transformer oil, whilst solid carbon dioxide was employed for the low temperatures. The magnetizing forces employed were 1 200 ampere-turns per cm. length for the cobalt specimens, 1 500 for the Al-Ni, and 2 500 for the Al-Ni-Co. The Al-Ni alloy cannot be magnetized to its fullest extent when in the horseshoe form because

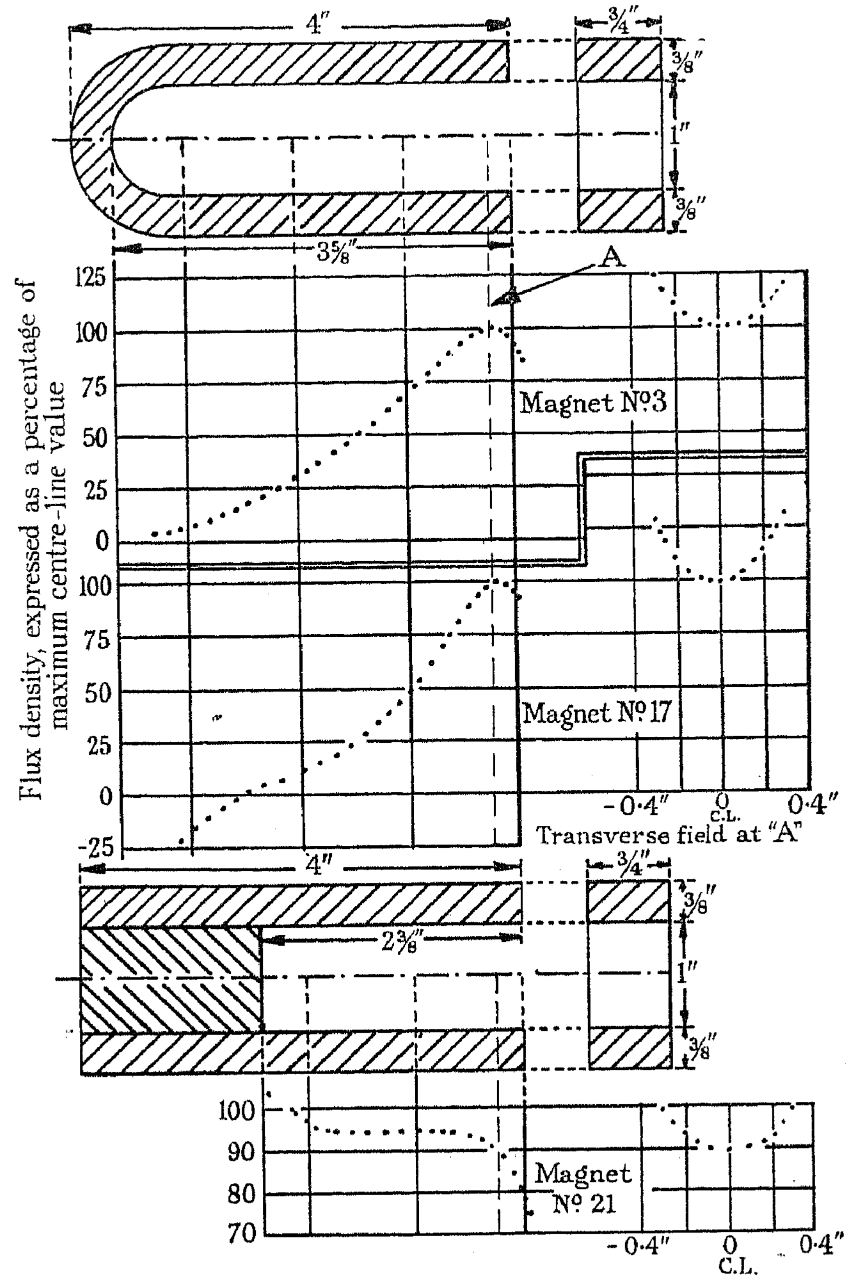

Fig. 4.—Variation of flux density in air-gap between limbs of horseshoe permanent magnets.

NOTE.—All distances measured in plane of magnet.

of the danger of formation of consequent poles, and, as it was, weak consequent poles were detected in all the magnets of this material, including the sample magnetized by the manufacturers.

The apparatus shown in Fig. 3 was designed to explore the field existing around the limbs of the magnets. A search-coil arrangement of the type already described was employed; the coil had 150 turns, each turn being a rectangle of about 0·75 cm. horizontal and 1·5 cm. vertical side. The coil was made smaller than that used in the tank apparatus because it was desired to determine the variation of field between the limbs of the magnets, and, since the flux density alters quite quickly with distance from the centre line, a small coil was essential. The magnet under test was placed upon a print on the

platform A, which could be set either horizontally or at 45° by means of the frame shown below it. The platform and frame were of geometrical design and stood upon the carriage B. The carriage could be moved measured distances sideways by the micrometer screw and wheel C, whilst the lengthways travel was adjusted by the screw and wheel D. The micrometer screws were of phosphor bronze and had 20 turns to the inch; the remainder of the apparatus was composed of brass. Although transverse measurements were made, the majority of the determinations were made along the centre line of the magnet between the poles. In an ordinary magnet, such as all of the cobalt samples, the centre-line field did not sink quite to zero as the coil approached the yoke (see Fig. 4 for typical fields). When the magnet possessed consequent poles, it was found that the field strength dropped to zero and began to increase with opposite sign before the yoke was reached (see Fig. 4). The value taken as 100 % in these diagrams was the maximum value obtained along the centre line. The Al-Ni-Co alloy magnets did not have poles in the usual position near to the ends of the limbs, since the limbs were made of mild steel. The field obtained with a magnet of this type is shown in Fig. 4. The fields were examined in the transverse direction in a line passing through the poles (in the case of magnets Nos. 3–19) and typical results are shown in Fig. 4. It will be noticed that the flux density at a distance of 0·2 in. from the limb surface was approximately 25 % greater than that on the centre line. It was impossible to get closer to the limb than this, but the curves appear to indicate that the density at the surface would be of the order of 75 % greater than that at the centre line. The reason for this field variation lies in the fact that the lines of force in the space between the limbs are curved and converge towards each limb. The search coil was calibrated, and the maximum field strength on the centre line expressed in gauss is given for each magnet in Tables 1 and 2. It was impossible to give such values for magnets Nos. 20 and 21, so that the values given are those at the point at which the measurements were made during the temperature cycles.

TEMPERATURE EXPERIMENTS

The magnet was put into the bath and, after the search-coil gear had been attached, readings were taken at atmospheric temperature. In the usual way this initial strength was taken as 100·00 %, and the subsequent values were calculated upon this basis. Temperature cycles were then carried out and readings were taken at small intervals of temperature. The cycles were continued until the pole strength at air temperature at the conclusion of a cycle was equal to the value at a corresponding temperature at the beginning of the cycle. When this happened, about three more cycles of the same type were performed. In general, the cycles to reach the steady state were carried out over the range 20° C. to 100° C., and then, after a few extra "steady state" cycles over the same range had been obtained, low-temperature cycles over the range 20° C. to − 60° C. were executed. This procedure was altered occasionally to make use of any carbon dioxide which happened to be available. It was found that in all cases, once the magnet had attained the reversible condition, there was no indication of temperature hysteresis. The strength was plotted against the temperature for each cycle (see the typical set of curves for magnet No. 14 shown in Fig. 5). It will be noticed that the magnet reached the steady condition after three cycles over the upper temperature range, which was a very common occurrence. The magnets were generally kept at 100° C. for about 15 min. during each cycle, so that most of them only had about an hour at this temperature before they attained the reversible condition. The manufacturers of the magnets had been requested to prepare the specimens right up to the point of magnetization and to ensure that the material should be structurally stable. Structural stability can be obtained by the method of Barus and Strouhal,* by keeping the material at 100° C. for a long period. The time to reach stability depends upon the ageing temperature employed, the previous heat-treatment, and the type of steel. The makers of the cobalt steel employed give the following figures: 15 % Co steel reaches stability after 600 hours at 100° C., whilst 35 % Co material requires approximately 1 800 hours at this temperature. The magnets used in this research never had much more than an hour at 100° C. during the experiments and showed magnetic stability after this treatment, so that it is safe to assume that the material employed had been properly treated by the manufacturers and was structurally stable.

The makers of the cobalt steel state in their handbook that, when the magnets are to be used for instruments, it is best to magnetize with the magnet in position with respect to its future iron circuit, to avoid the demagnetizing effects of other iron circuits or open-circuit conditions. It is stated that such magnets should be left for a period varying from 3 to 8 weeks from magnetization before the instrument is calibrated. The period between magnetization and the first test cycle is given in Tables 1 and 2, the time in the case of those supplied already magnetized being that between the date of receipt and the first test.

The experimental history of each magnet is given in Tables 1 and 2. The strength values at 20° C., 100° C., or − 60° C. were read off the strength/temperature curves for each cycle, and curves of the zigzag type shown in the lower portion of Fig. 5 were drawn. On the latter curve, the dots represent the values of the magnetic strength at 20° C. and at the extreme temperature of each cycle, i.e. the point plotted against the abscissa zero is the strength at the beginning, the point at "1" is the strength at 107° C. at the maximum temperature attained in the first cycle, the value at "2" is that at 20° C. at the end of the cycle, the value at "3" is that at the extreme temperature of the next cycle, and so on. The points have been joined by straight lines and then the values measured on the cycle curves at 100° C. or at − 60° C. have been marked with a cross on their corresponding zigzag line. The crosses have been connected by the three thick lines shown, and the magnet has attained the steady condition when these lines become horizontal. Curves of this type can be employed to determine the permanent loss of magnetic strength occurring during the initial cycles. Tables 1 and 2 give the percentage permanent loss occurring during each cycle, together with the total loss.

* See Bibliography, (7), (8).

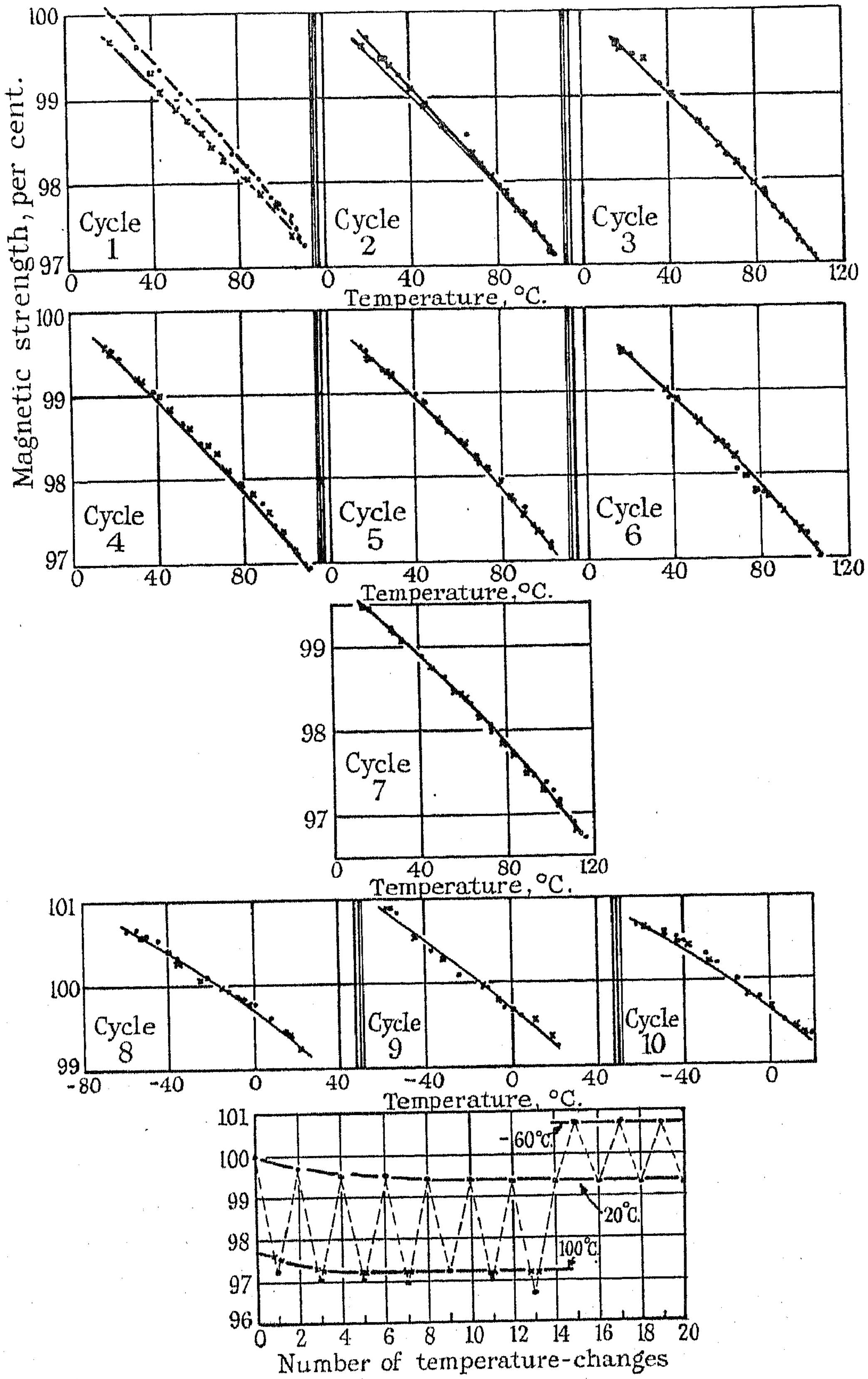

Fig. 5.—Typical strength/temperature curves for magnet No. 14.

When the magnet had reached the reversible state, there was no further permanent loss of strength and then all subsequent readings were plotted together on one strength/temperature curve (see Fig. 6). In all cases these points gave indication of a continuous relationship of the second order extending from $-$ 60° C. to 100° C., and a mean line was drawn through them. The line was the best possible consistent with an equation of the second-order type, and the two constants a and b were calculated for each magnet and are given in Tables 1 and 2. The constants a and b refer to the type of equation:—

$$H_\tau = H_0(1 + a\tau + b\tau^2)$$

where H_τ is the strength at τ° C. and H_0 that at 0° C. It was found that in all cases both a and b were negative.

TESTS ON COBALT-STEEL MAGNETS

General

Tests were made upon six 15 % Co-steel magnets, and two each of 3 %, 6 %, 9 %, and 35 % Co; the reference numbers of the samples and their composition are given in Table 1.

Magnets No. 4, 5, 8, and 11, were tested first of all over the lower temperature range down to $-$ 60° C. Magnet No. 4, a 15 % Co-steel magnet magnetized at 20° C.,

showed a slight permanent loss (0·06 %) during the first cycle, and after that there was no further loss. Magnet No. 5, a 15 % Co-steel magnet magnetized at 160° C., suffered a loss of 0·30 % during the first cycle, which was over the lower range, but showed no loss during the next cold cycle. The next few cycles were over the upper range to 100° C.; there was no apparent loss during the first of them, but a slight loss occurred during the next two, after which the magnet appeared to have reached the reversible condition.

Magnet No. 6 was magnetized at 106° C. and suffered losses during the first two cycles, which were over the upper range of temperature. After this no further losses occurred.

Magnet No. 7, which was a 15 % Co-steel magnet magnetized at − 66° C., was tested first of all over the upper temperature range, but showed no trace of permanent loss during any of its cycles.

Magnet No. 8, which was a similar magnet magnetized at − 70° C., experienced permanent losses (0·60 %) during its first two cycles, which were down to − 60° C., and appeared to have reached the reversible condition by the third cycle of that type. The cycles following were over the upper temperature range, and further losses occurred before the magnet attained the steady condition. When still further cold cycles were tried, the magnet suffered no losses.

A 6 % Co-steel magnet, No. 11, magnetized by the makers, also showed losses during the first cold cycles and then attained the reversible condition, but experienced further losses when higher temperature cycles were employed. It therefore appears that, with cobalt-steel magnets of this type, those which attained the reversible condition by means of a series of cold cycles were not in the steady state for the upper temperature cycles. On the other hand, the other cobalt magnets (Nos. 3, 6, 7, 9, 10, 12, 13, 14, 15, and 16) showed that a magnet aged by a series of cycles over the temperature range to 100° C. was also in the reversible condition with regard to any subsequent cycles over the lower temperature range. Although the initial cold cycles applied to the magnets Nos. 5, 8, and 11, produced a reversible condition which was not maintained when the specimens were subjected to high temperature cycles, it was found that, after these magnets had reached the steady state by a series of cycles of the type 20° to 100° C., the reversible condition was maintained when they were subjected to further cycles down to − 60° C. It therefore appears that the best cycle for ageing is that up to 100° C., and that this ageing is maintained whatever the subsequent treatment of the magnet, whereas ageing over a lower temperature cycle does not persist.

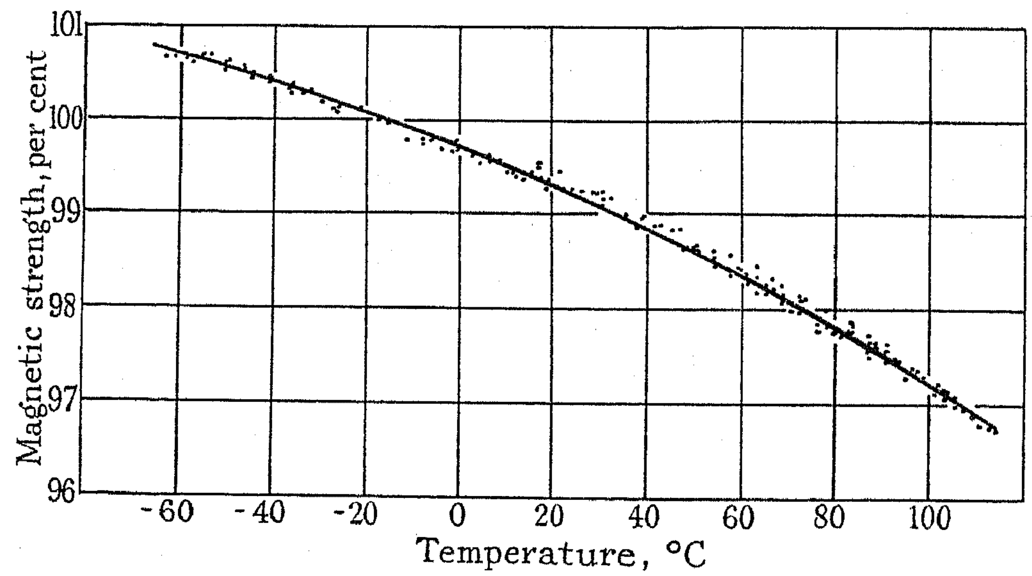

Fig. 6.—Typical composite "steady-state" strength/temperature curve for magnet No. 14 (9 % cobalt steel).
Curve represents $H_T = H_0\,[1 - 0{\cdot}0_3\,1\,975_T - 0{\cdot}0_6\,533_T{}^2]$

15 % Cobalt Magnets

Table 1 and Figs. 7 and 8 show the effects produced by change of magnetization temperature. The temperature coefficient a had a value of − 0·000215 at a magnetization temperature of − 70° C., and − 0·000208 at 20° C., whilst magnetizing at 100° C. produced a coefficient of − 0·000224. This result is supported by the work of Gray and Higgins,* who found that a specimen magnetized at liquid-air temperature, − 190° C., had a higher temperature coefficient than a sample magnetized at room temperature. It will be noticed that with the 15 % Co-steel magnets a magnetization temperature of 20° C. gave a minimum temperature coefficient, a fact which is particularly useful since that is the most usual temperature for magnetization. The coefficient b showed no connection with magnetization temperature; its value was of the order of − 0·00000025 to − 0·00000085. Although these values are small, it must be remembered that the coefficient is multiplied by the square of the temperature in Centigrade degrees, so that the effect can be quite considerable when the temperature is very different from 0° C.

In paragraph (viii) of the summary of early work, on page 728, it was recorded that the temperature coefficient depends upon the intensity of magnetization. The demagnetizing forces acting upon a magnet depend upon the dimensions and the intensity of magnetization, so that for magnets of similar size and made of the same material it follows that the temperature coefficient, which depends upon the demagnetizing forces and the coercive

* See Bibliography, (26).

force of the material, will depend upon the intensity of magnetization. The exact relationship between the coefficient and the intensity is probably linear, but has not been determined for the range of materials employed in modern magnets. Several experimenters* have found that there is a connection between the two factors. It is possible to apply a correction to the results shown in Fig. 7 by altering the coefficients in direct proportion to the intensities measured at 20° C. when the magnets were aged, and bringing them all to the intensity value obtained with the specimen magnetized at 20° C. This correction gave the broken line in the diagram, but the shape of the original curve was preserved.

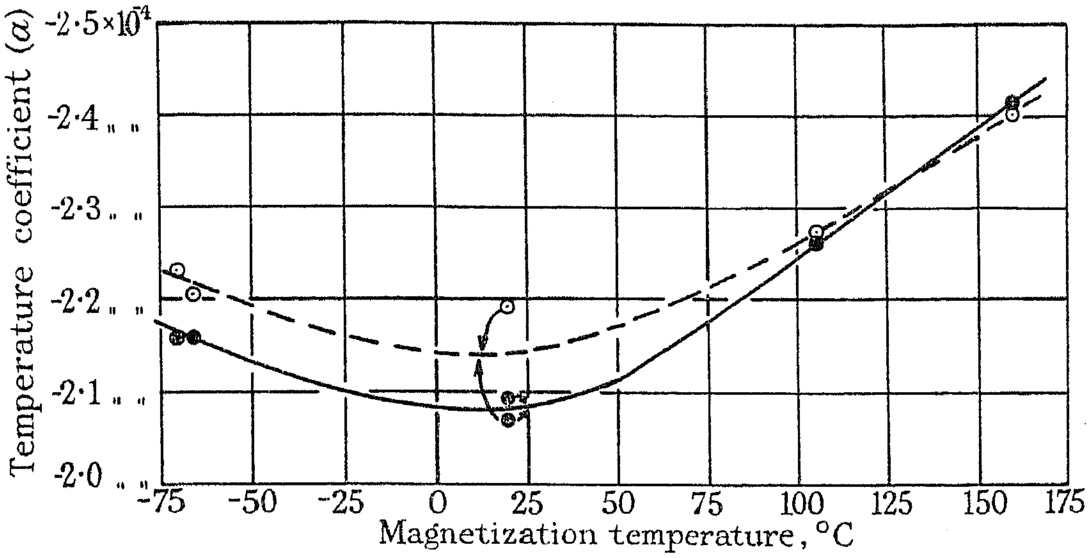

Fig. 7.—Variation of coefficient " a " with magnetization temperature, for 15 % cobalt steel.
——●—— Experimental results.
---⊙--- Experimental values corrected for intensity of magnetization.

triangles refer to those subjected initially to high temperature cycles, the latter being the treatment usually employed in ageing magnets. From the steam ageing point of view, it appears best to use a low magnetization temperature to get smaller losses, a result which is in agreement with the work of C. C. Trowbridge.* The strange effects produced by the use of cold cycles cannot be explained.

Effect of Cobalt Content

In considering the results of this section of the work, it must be emphasized that the 35 % Co-steel magnets had a different chemical composition from the other samples (5 % Cr, as compared with 9 % in magnets Nos. 3–14; and 5 % Wo, whereas the other specimens had none at all). In addition to this, as has been mentioned already, the last stage of the triple heat treatment was different in the case of the 35 % Co-steel magnets. The total effect of the differences of composition and heat treatment would be to give the steel a different structure,

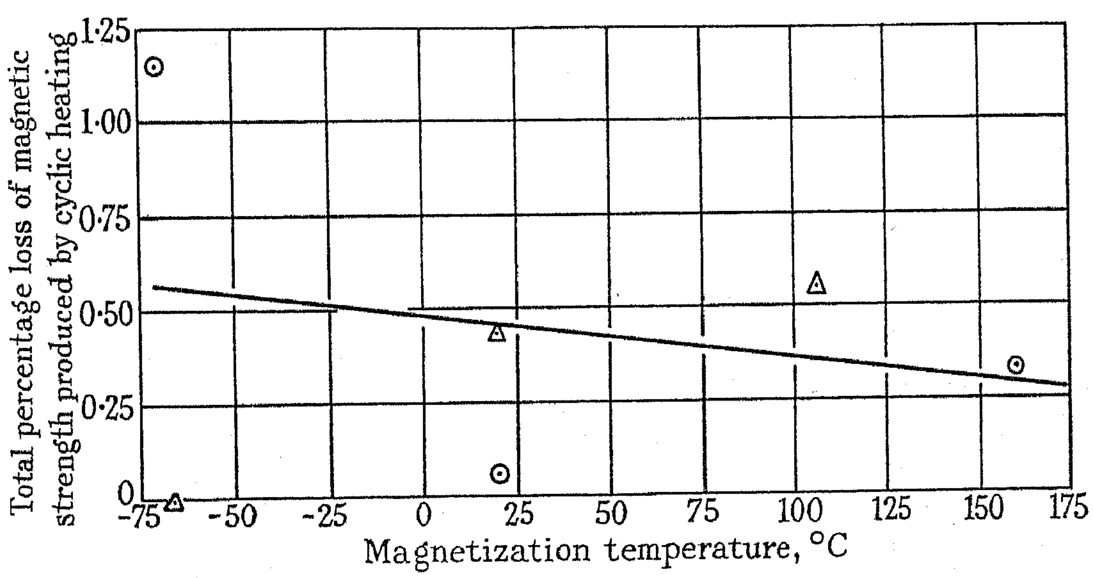

Fig. 8.—Variation of total permanent loss of magnetic strength with magnetization temperature, for 15 % cobalt steel.
△ Magnet subjected initially to cycles of the type 20° C. to 100° C.
⊙ Magnet subjected initially to cycles of the type 20° C. to −60° C.

Fig. 8 shows the effect of alteration of the magnetization temperature upon the permanent loss of magnetic strength produced by the temperature cycles. The results appear rather scattered, but it must be remembered that the loss values were shown to depend upon the type of cycle performed initially. The circles in Fig. 8 indicate magnets given cold cycles initially, whilst the

* See Bibliography, (6), (16), (25), (39).

* See Bibliography, (22), (23).

and it is to be expected that the 35 % Co-steel specimens would behave in rather a different manner from the rest. So far as the temperature coefficient a is concerned, the 35 % Co samples appear to conform to the general trend of the results, but their points on the curve of permanent loss produced by heating should be considered separately from the others. For this reason, the last portion of the curve is shown dotted in Fig. 10. Figs. 9 and 10 are intended to show the results obtained with the ordinary materials as supplied by the manufacturers.

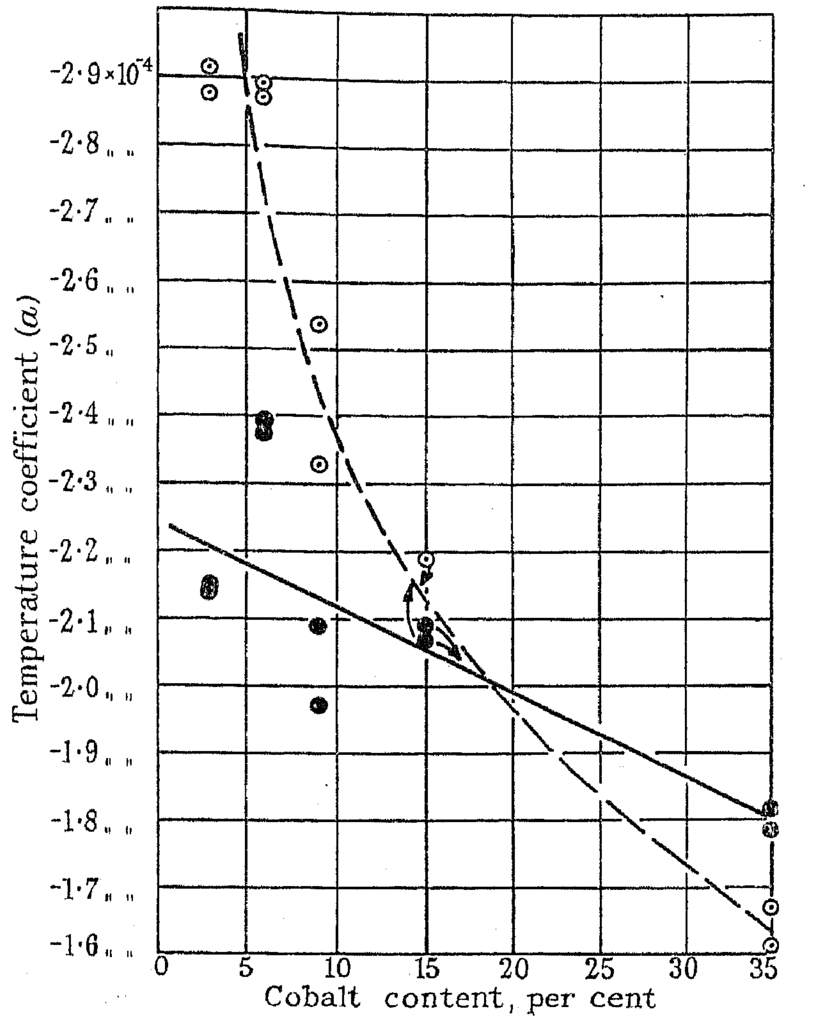

Fig. 9.—Variation of coefficient " a " with cobalt content of cobalt steels.

——●—— Experimental results.
---⊙--- Experimental values corrected for variation of the intensity of magnetization.

Fig. 9 shows the effect of alteration of cobalt content upon the coefficient a. The dotted curve is of the results as corrected for the variation of the intensity of magnetization. The curves are rather different, but the general trend indicates that the coefficient falls with increase of cobalt content. The points shown for the 15 % Co steel are for the magnets Nos. 3 and 4, which were magnetized at ordinary temperatures. It has been mentioned already that, assuming the demagnetizing forces (i.e. the dimensions and intensity of magnetization) are constant, the temperature coefficient will depend upon the resistance to demagnetization, which is really the coercive force. The apparatus available was unsuitable for the measurement of remanence and coercive force, so that reliance had to be placed upon the average values of the coercive forces of the various cobalt alloys as supplied by the manufacturers. These figures are given in Table 3 together with the values of a corrected for

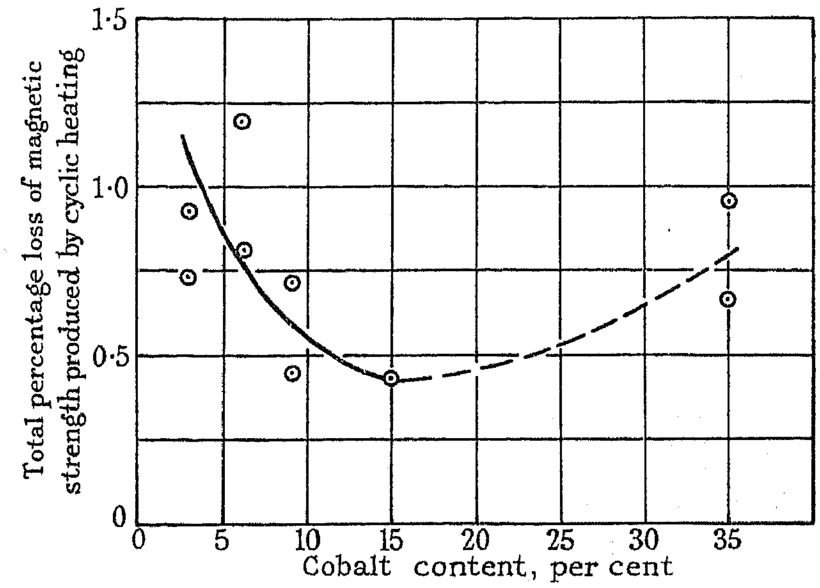

Fig. 10.—Effect of cobalt content of cobalt steels on the total permanent loss of magnetic strength produced by cyclic heating.

Table 3

COBALT-STEEL MAGNETS: TO SHOW THAT $\frac{(\text{TEMPERATURE COEFFICIENT } a) \times (\text{COERCIVE FORCE})}{(\text{INTENSITY OF MAGNETIZATION})} = \text{CONSTANT}$

Magnet number	Cobalt content	Maximum flux density on magnet centre-line (J)	Temperature coefficient a	Corrected value of a* ($75\cdot49\ a/J$)	Coercive force (H_c)	aH_c/J
	per cent	gauss			oersteds	
9	3	56·39	$-2\cdot147 \times 10^{-4}$	$-2\cdot874 \times 10^{-4}$	135	$5\cdot14 \times 10^{-4}$
10	3	55·75	$-2\cdot153 \times 10^{-4}$	$-2\cdot915 \times 10^{-4}$	135	$5\cdot21 \times 10^{-4}$
11	6	62·55	$-2\cdot399 \times 10^{-4}$	$-2\cdot895 \times 10^{-4}$	150	$5\cdot75 \times 10^{-4}$
12	6	62·44	$-2\cdot373 \times 10^{-4}$	$-2\cdot869 \times 10^{-4}$	150	$5\cdot70 \times 10^{-4}$
13	9	62·32	$-2\cdot093 \times 10^{-4}$	$-2\cdot535 \times 10^{-4}$	165	$5\cdot54 \times 10^{-4}$
14	9	63·82	$-1\cdot975 \times 10^{-4}$	$-2\cdot336 \times 10^{-4}$	165	$5\cdot11 \times 10^{-4}$
3	15	72·06	$-2\cdot093 \times 10^{-4}$	$-2\cdot193 \times 10^{-4}$	195	$5\cdot66 \times 10^{-4}$
4	15	75·49	$-2\cdot069 \times 10^{-4}$	$-2\cdot069 \times 10^{-4}$	195	$5\cdot34 \times 10^{-4}$
15	35	83·75	$-1\cdot787 \times 10^{-4}$	$-1\cdot611 \times 10^{-4}$	255	$5\cdot44 \times 10^{-4}$
16	35	82·18	$-1\cdot818 \times 10^{-4}$	$-1\cdot670 \times 10^{-4}$	255	$5\cdot64 \times 10^{-4}$

* The corrected values of a are altered in proportion to the ratio of their magnetization intensity to that of magnet No. 4.

intensity of magnetization. The last column of the Table gives the product of the coercive force and corrected a, and it will be noticed that the values are approximately constant. This fact confirms the suggestion that the temperature coefficient depends upon the intensity of magnetization, i.e. the demagnetizing force, and the coercive force, the relationship being expressible by the equation $a = KJ/H_c$ when the dimensions are maintained constant. In this equation K is a constant, J the intensity of magnetization, and H_c the coercive force of the material. The equation would not be universal in

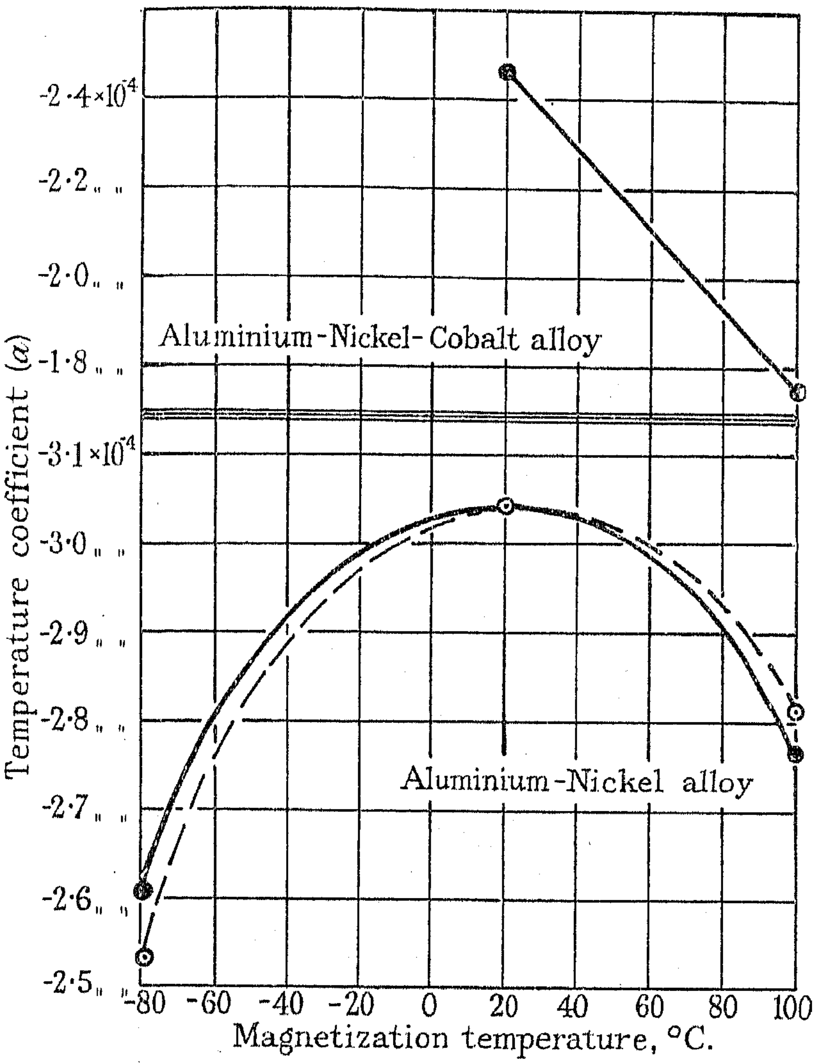

Fig. 11.—Variation of coefficient "a" with magnetization temperature, for aluminium alloys.

——●—— Experimental results.
---○--- Experimental values corrected for variation of the intensity of magnetization.

regard to values, since K would only hold for one set of dimensions. The demagnetizing factor of a magnet depends upon the dimensions; such factors are very difficult to calculate, and there are no figures available for horseshoe magnets.

Fig. 10 shows the influence of the cobalt content upon the total permanent loss produced by cyclic heating. The minimum loss appears to occur with the 15 % Co-steel, but the results given by the 35 % Co-steel specimens may not be comparable with those of the other materials, for the reasons already mentioned.

ALUMINIUM-NICKEL ALLOY

The Al-Ni alloy employed in this research is a typical sample of these materials; its composition is given in Table 2, and the results are shown in Figs. 11 and 12.

A number of references to the production and treatment of materials of this type are given in the Bibliography.

Magnet No. 17 was supplied in the magnetized condition, whilst Nos. 18 and 19 were obtained ready for magnetization, and this was done at − 79° C. in the case of No. 18 and at 100° C. for No. 19. The experimental history of each sample is given in Table 2, and there was nothing of special interest in the curves of the individual cycles. The initial experiments in all three cases were over the upper temperature range, and with magnets Nos. 17 and 19 stability was attained in two cycles.

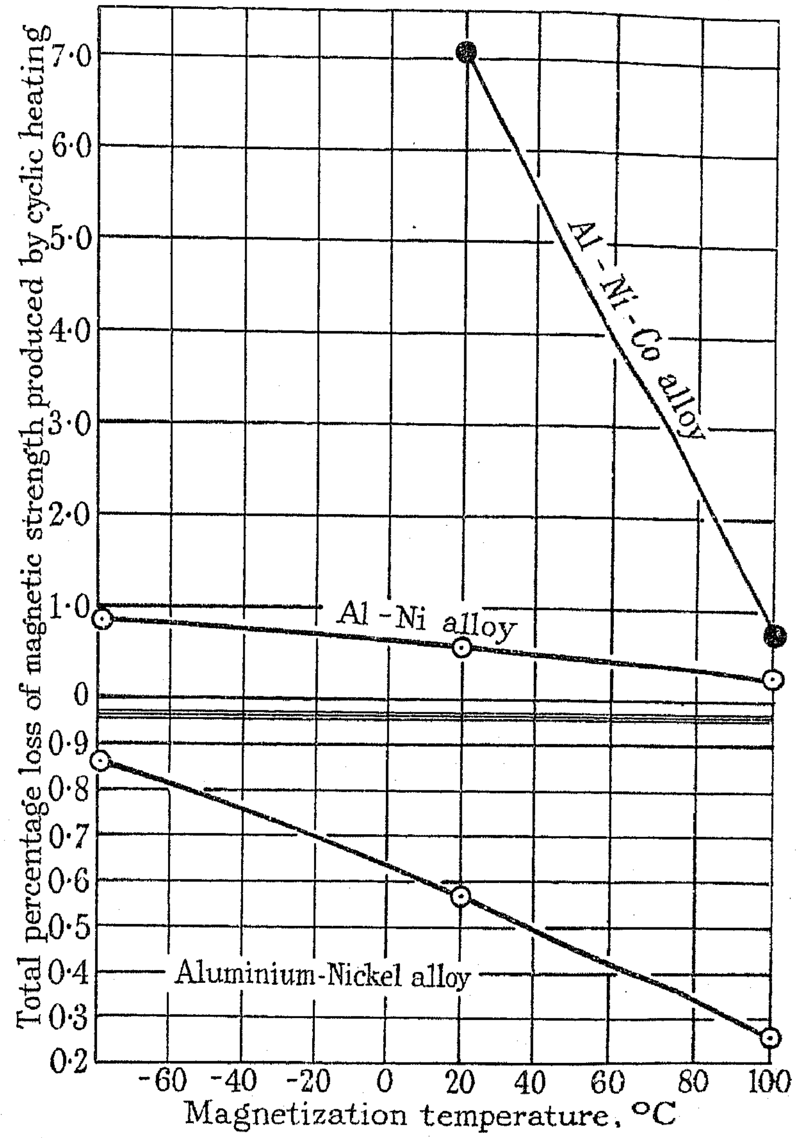

Fig. 12.—Variation of total permanent loss of magnetic strength with magnetization temperature, for aluminium alloys.

Magnet No. 18, magnetized at − 79° C., did not attain the reversible condition until the fourth cycle, and gave the maximum permanent loss of strength. The curve of Fig. 12 shows that the loss decreased as the magnetization temperature was raised, a result also exhibited by the Al-Ni-Co alloys.

The temperature coefficients a and b were calculated for the best lines through the experimental points, and the a values were a good deal higher than those obtained with the cobalt-steel magnets, − 0·00026 to − 0·00030 as compared with − 0·00018 and − 0·00024 for the cobalt specimens. On the other hand, the b coefficients of the Al-Ni alloy were lower, indicating that the magnetic-strength/temperature curves were more nearly straight. The coefficient a is shown plotted against the magnetization temperature in Fig. 11, and it appears

that the highest value is obtained at a magnetization temperature of 20° C. Correction of the coefficients with respect to the intensity of magnetization does not greatly affect the shape of the curve, which is the opposite of that obtained with the 15 % Co-steel magnets. It would be inadvisable to lay down hard-and-fast rules for the Al-Ni magnets from these results, since there were only three samples, but it does appear that magnetizing at atmospheric temperature produces the highest temperature coefficient.

ALUMINIUM-NICKEL-COBALT ALLOY

The composition of the Al-Ni-Co alloy is given in Table 2, and details of the dimensions of the built-up magnets are given in Fig. 4. Magnet No. 20 was supplied in the magnetized condition; the other specimen, No. 21, was received ready for magnetization, and this was done at 100° C. Both magnets were subjected to high-temperature cycles initially and these were continued until the reversible condition was attained, and then several cold cycles were executed. Magnet No. 20 lost 6·0 % of its strength during the first hot cycle, whilst No. 21 only lost 0·7 %. The permanent losses sustained during each cycle are given in Table 2, and it will be noticed that the magnets did not reach the steady state until the fourth cycle. When cold cycles were tried, after the attainment of the steady state, magnet No. 21 behaved in the customary manner and suffered no further permanent loss of strength. On the other hand, No. 20 experienced a loss of approximately 0·2 % during the first cold cycle, but showed no further change after that; this was the only magnet of all those used in the research which exhibited this effect. The phenomenon may be due to the molecular structure of the material. The strength/temperature values obtained after specimen No. 20 had again attained the reversible condition during the cold cycles were raised to correspond to the readings obtained during the "steady state" hot cycles in order to get a continuous curve covering the full temperature range from which the coefficients were computed. This appeared to be in order since the loss caused by the first cold cycle was quite small. The strength/temperature curves had the usual shape, but the b coefficients were rather larger than those obtained with the Al-Ni alloy (see Table 2). Fig. 11 shows that a high magnetization temperature appears to give a low a coefficient, a result agreeing with that obtained with the Al-Ni specimens, but which is opposite to that obtained with the 15 % Co-steels. The a coefficients were lower than those of the Al-Ni magnets, and were really surprisingly small considering the small length/breadth ratio of the actual piece of alloy material in each built-up magnet.

GENERAL REMARKS

It should be pointed out that, in view of the necessity for making field-strength measurements between the limbs of the horseshoe magnets, it was impossible to carry out the heating tests with the magnets supplied with the type of iron circuit with which they would be used in electrical instruments. Since the magnets had to be tested under open-circuit conditions, it is certain that the temperature coefficients would not be equivalent to those operating when the magnets had different iron circuits. Earlier research has shown that dimensions have a very considerable effect upon the temperature coefficient, since the demagnetizing force depends upon the size of the magnet. The results given in this paper must be considered with due regard to the dimensions of the magnets employed. The magnets used in the tests were of a type frequently employed in electrical instruments, and it is therefore hoped that the figures will be of some use in that connection.

It would be of little use to attempt to develop a theory in connection with the research, because, for one thing, the alloys employed for these modern magnets are very complex and are subjected to complicated heat-treatments. Honda and Matumura* have suggested a theory connecting length/breadth ratios and temperature coefficients, and the reader is referred to the original paper for details. At the present time a large amount of research is being done upon the magnetic properties of single crystals of ferromagnetic materials, and it may be possible to apply the results to complex alloys.

It is a well-known fact that a magnet never actually works at the flux value known as the remanence, but that the working flux density depends upon the dimensions of the magnetic circuit, which includes air-gaps, and on the material employed. The useful flux in the gap demagnetizes the magnet, and the process continues until the demagnetizing forces are equal to the magnetomotive force of the magnet. The working point of the magnet is thus somewhere on the B–H curve between the remanence and the coercive-force points. It would be interesting to determine what happens to the working point on the demagnetization curve when the temperature of the magnet is altered, assuming the magnet is already aged. Does the point move along the actual curve, or are there a family of B–H curves, one curve corresponding to each temperature, and with working points on each of them, so that the actual working point merely moves from one curve to the next as the temperature is changed? The change in strength of the magnets used by the author was of the order of 2 % to 3 % for a temperature-change of 100 deg. C., and it is to be expected that the movement of the point on the B–H curve would be of comparable magnitude. Present-day magnetic measurements are rather too crude to permit measurements of such a shift.

CONCLUSIONS

The results obtained in the research can be summarized as follows:—

(1) General

(i) With one exception, it was possible to put the permanent magnets into the reversible condition as regards variation of strength with temperature, by several cycles of the type 20° C. to 100° C. The steady state attained in this way was maintained when the magnets were subjected to cycles of the type 20° C. to — 60° C.

(ii) Cobalt-steel magnets only were subjected to cold cycles initially, and it was found that the reversible state could be attained by two or three cycles, but this condition was not maintained when the magnet was subjected to higher temperatures.

* See Bibliography, (40).

(iii) Magnets which had given the results recorded in (ii) could be put into the true reversible condition by high-temperature cycles, and then the state was maintained throughout the range $-60°$ C. to $100°$ C.

(iv) There was no evidence of a temperature hysteresis effect.

(v) When a magnet had attained the true steady state it was found that there was a definite relationship between strength and temperature throughout the range $-60°$ C. to $+100°$ C., expressible by the equation

$$H_\tau = H_0(1 + a\tau + b\tau^2)$$

where H_τ is the strength at $\tau°$ C., H_0 that at $0°$ C., and a and b are constants which are always negative.

(2) 15 % Cobalt-Steel Magnets

(i) The general trend of the values of the permanent loss of magnetic strength produced by cyclic heating appears to indicate that less loss occurs when the magnet is magnetized at a high temperature. If, however, we consider only those magnets aged by high temperature cycles, it then seems that a very low magnetization temperature is an advantage.

(ii) The coefficient a appeared to be affected by the magnetization temperature, and gave a minimum value at $20°$ C.

(3) Cobalt-Steel Magnets

(i) The value of a was found to be of the order of $-0{\cdot}00018$ to $-0{\cdot}00024$, whilst b varied from $-0{\cdot}00000025$ to $-0{\cdot}00000083$.

(ii) a was found to be reduced by increase of the cobalt content. Increase of the cobalt content increases the coercive force, and it was found that

$$\frac{a \times \text{Coercive force}}{\text{Flux density between limbs}} = \text{Constant}$$

The particular value of the constant would only hold for magnets of the same dimensions.

(iii) The permanent loss of magnetic strength was reduced by increase of the cobalt content from 3 % to 15 %. The 35 % Co-steel gave a higher loss than the 15 % Co-steel specimens, but the steel was of a different type from the others used.

(4) Aluminium-Nickel Alloy

(i) The coefficient a was greater than that of the cobalt specimens, and was of the order of $-0{\cdot}00026$ to $-0{\cdot}00030$. The coefficient b varied from $-0{\cdot}00000020$ to $-0{\cdot}00000043$, and the strength/temperature curves were straighter than those of the cobalt samples.

(ii) The coefficient a was affected by the magnetization temperature and appeared to have a maximum value at a magnetization temperature of $20°$ C.

(iii) The total permanent loss of magnetic strength caused by the cyclic heating appeared to be affected by the magnetization temperature and to fall as it was increased.

(5) Aluminium-Nickel-Cobalt Alloy

(i) Two specimens were tested. One stabilized over the range up to $100°$ C. was also stable when subjected to cycles from $20°$ C. to $-60°$ C.; the other suffered a slight loss.

(ii) The value of a was comparable with the values for the cobalt steels, but b was found to be higher than usual.

(iii) a appeared to be reduced by increase of magnetization temperature.

(iv) The magnet which had been magnetized at air temperature suffered a greater permanent loss than that which had been magnetized at steam temperature.

ACKNOWLEDGMENTS

The experimental work in connection with this paper was performed in the Electrical Engineering Department of the Northampton Polytechnic Institute, and the author would like to express his gratitude to the governing body of the Polytechnic and to the London County Council for providing the facilities for the research. In particular, the author is indebted to the late Mr. A. C. Jolley for the great interest he showed in the work and for much helpful advice and criticism. Thanks are also due to Mr. Harrison and the staff of the Polytechnic Instrument Workshop, who constructed the bulk of the apparatus employed. The aluminium-alloy magnets were kindly provided by Mr. D. A. Oliver, B.Sc.(Eng.), who also furnished the author with details of the composition and treatment of the materials.

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INTERNATIONAL COMPARISON OF IMPULSE-VOLTAGE TESTS*

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(*Paper first received* 31*st May and in final form* 3*rd September*, 1937.)

SUMMARY

A number of impulse-voltage tests have been made under the auspices of the International Electrotechnical Commission in certain high-voltage laboratories in Europe. The tests were devised to ascertain the extent of agreement which can be reached on the measurement of impulse voltages at the present time, and to act as a guide to the Commission in framing a specification for impulse-voltage testing of electrical apparatus. The dispersion of results obtained on the measurement of the sparkover voltage of a simple test gap in eight European laboratories is at present very wide, being as great as $\pm$ 8 %, though good agreement exists between the average values so obtained and the average values for similar tests recently published in the U.S.A. The tests on line insulators also reveal a wide diversity of results, but it has been established that insulators which have successfully withstood power-frequency voltage tests may sometimes be fractured by impulse voltages, and sufficient information is now available to warrant the introduction of impulse-voltage tests on line insulators by the I.E.C.

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(1) Introduction.
(2) Comparison of Impulse-Voltage Tests on a Simple Air-gap.
(3) Comparison of Impulse-Voltage Tests on Insulators.
(4) Conclusions.

(1) INTRODUCTION

The International Electrotechnical Commission has for some years had under consideration the introduction into the standard specifications of clauses relating to the impulse-voltage testing of electrical apparatus. Two years ago, at the 1935 Brussels meeting of the I.E.C., the recommendations of the Sub-Committee on Impulse Voltages relating to the nomenclature and general principles of impulse-voltage testing were accepted and the Sub-Committee was requested to make further recommendations on the testing of line insulators and bushing insulators.

It was admitted that the measurement of impulse voltages presented a number of difficulties and that these difficulties probably accounted for the wide diversity of published results on the measurement of sparkover of line insulators. The Sub-Committee therefore decided that before proceeding further with the framing of an international specification it would be advisable to ascertain the extent of agreement which could be reached on the determination of the sparkover characteristics of a simple air-gap under strictly controlled conditions. This would act as a pointer to the order of accuracy which might reasonably be expected at the present time in impulse-voltage testing. It was decided to examine the characteristics of a gap between two horizontally-mounted steel rods, a type of gap easy to construct and simple to define, and one for which several American impulse-voltage calibrations were available. A specification for the gap and the tests was issued by the Sub-Committee, and tests were made in eight different European laboratories. The results are given in Section (2) of this paper, and comparison is there made with results recently published in the U.S.A. for similar tests performed in five American laboratories.

The Sub-Committee further decided that information should be collected on the general ability of insulators to withstand impulse voltages of varying crest-values and wave-shapes, before a standard test was specified for line insulators. It is known, for example, that the impulse ratio of sparkover for most insulators is higher for impulses of negative polarity than for those of positive polarity, and it is also known that insulators are more frequently punctured by negative impulses than by positive impulses. A specification will have to define the polarity, shape, and crest value of the test voltage and the number of times the test may be applied without causing damage to a good insulator. It was agreed that, instead of a number of insulators being circulated to the participating laboratories engaged on the tests, insulators should be selected at random so as to give a more comprehensive survey of insulator characteristics; and that tests should include the determination of the minimum impulse sparkover with different wave-shapes, and the general ability to withstand voltages in excess of the minimum sparkover values. The results of the investigations are set out in Section (3) of this paper.

The laboratories engaged in making some or all of the above tests for the I.E.C. are as follows:—

(A) University of Brussels.
(B) Hermsdorf-Schomburg Isolatoren Gesellschaft: Hermsdorf.
(C) Metropolitan-Vickers Electrical Company: Manchester.
(D) Società Italiana Pirelli: Milan.
(E) University of Padua.
(F) Compagnie Générale d'Électro Céramique: Paris.
(G) Allmänna Svenska Elektriska Aktiebolaget: Ludvika.
(H) Ateliers de Constructions Électriques de Charleroi.

For the sake of brevity these laboratories will be referred to in the following sections by their letters only.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

(2) COMPARISON OF IMPULSE-VOLTAGE TESTS ON A SIMPLE AIR-GAP

If a specification for impulse-voltage tests calls for the determination of the minimum impulse sparkover of the object under test, it is well known that the sparkover will most probably occur on the wave-tail of the impulse. The sparkover voltage will therefore be dependent upon the duration of the wave-tail, and to a much less degree upon the duration of the wave-front: it will be influenced by humidity as well as by air density. All the above factors influence the sparkover characteristics of the simple air-gap chosen for the comparative tests, so that the accuracy of determination of sparkover of the gap is representative of the accuracy of determination of the sparkover of electrical apparatus such as line and bushing insulators.

The electrodes of the test gap consisted of two steel rods of $\frac{1}{2}$-in. to $\frac{5}{8}$-in. square cross-section cut perpendicular to their length, the corners being left sharp, not rounded with a file. The electrodes were supported horizontally in the same straight line and at a distance above ground between $1\frac{1}{2}$ and 2 times the spacing of the electrodes for any one test. The electrodes were supported in general on porcelain pedestal insulators, and for all tests were made to overhang clearly from the supports by a distance of not less than half the electrode spacing. One electrode was earthed, the other connected to the impulse generator. The applied impulses had wave-fronts of 1 microsecond duration with a tolerance of $\pm$ 50 % (the wave-front duration is given by 1·25 times the time-interval between the points on the wave-front where the voltage is 10 % and 90 % respectively of the crest voltage); and wave-tails of 5 and 50 microseconds time-to-half-value with a tolerance of $\pm$ 20 % were employed. Oscillograms showed that the amplitude of oscillations superimposed on the wave-crest was less than 5 % of the crest amplitude and, in all cases, adherence to the 1/5 and 1/50 wave-shapes was closer than the extreme values permitted by the agreed tolerance. Adjustment of the crest voltage of the applied wave was made until sparkover took place at nearly every application of the applied impulse [approximately 90 % sparkover to comply with the I.E.C. provisional (1935) definition of the "minimum impulse (90 %) sparkover"]. Not less than 50 impulses were applied to verify the estimated sparkover voltage. The voltage was measured in all laboratories by the sphere-gap in the absence of any agreed alternative measuring device, and the calibration curves for the sphere-gap provisionally adopted by the I.E.C. in 1935 were employed with the proviso that the sphere-gap should not be used at a spacing in excess of the sphere radius. For the determination of the crest value of the applied voltage the sphere-gap was adjusted until the sparkovers were evenly distributed between the test gap and the sphere-gap, and 20 impulses were applied to verify the sphere-gap adjustment. All other objects were spaced at distances from the test gap greater than twice the gap spacing.

During the tests the atmospheric pressure, temperature, and humidity, in the neighbourhood of the test gap were noted. It is presumed with fair justification that the test-gap sparkover voltage varies with pressure and temperature in the same manner as does the sphere-gap sparkover voltage, so that no correction to the sphere-gap curve is necessary in determining the sparkover-voltage/spacing curve of the test gap. This is not the case, however, for humidity: a correction factor is applicable to the test-gap sparkover voltage but not to the sphere-gap sparkover voltage. Unfortunately there is very little evidence of the manner in which sparkover is influenced by humidity for the conditions of sparkover adopted by the Sub-Committee. The latest information, due to Fielder,* shows that the effect of humidity on sparkover of a rod-gap similar to that used in these investigations depends upon wave-shape, polarity, and the amount of over-voltage in excess of the minimum sparkover voltage. For a positive 1/50 wave, the correction factor for the minimum sparkover voltage amounts to 1·09 % of the measured voltage for every gramme of water vapour per cubic metre of air above or below the standard humidity of 11 g. per m³ adopted by the I.E.C., the correction factor being positive for humidities below standard value.† This factor falls as the voltage is increased above the minimum value as defined by Fielder. The minimum (90 %) sparkover voltage as determined by the I.E.C. provisional definition is probably some 5 % to 7 % in excess of that defined by Fielder, but no exact information is available as to the value of the humidity correction factor at these slightly higher voltages. The values of sparkover given below have therefore had to be corrected according to Fielder's curves, and where the humidity has been very high or very low the values are probably in error by amounts up to 2 %. It should further be noted that Fielder's curves apply to a $1\frac{1}{2}/40$ wave: for a 1/50 wave the correction factor will be slightly larger than Fielder's factor, thus partially offsetting the error previously mentioned.

The humidity correction factors employed for the $\pm$ 1/50 and $\pm$ 1/5 wave for the rod-gap are given in Figs. 1 and 1A, the first expressing the humidity in grains per cubic foot of air, the second in grammes per cubic metre of air, the Continental standard. The I.E.C. standard of absolute humidity corresponds to a relative humidity of 64 % at 20° C. (68° F.). A ready conversion table from relative humidities at various temperatures to absolute humidities is given in Fig. 2.

The results of the comparative tests are given in Figs. 3–6 for both wave-shapes and both polarities. Mean curves are given in Fig. 7. The results are given for a temperature of 25° C. From the mean values the maximum deviation amounts to 10 % for the $\pm$ 1/50 waves, corresponding to a standard deviation from the mean of $7\frac{1}{2}$ %. The maximum deviation for the $\pm$ 1/5 waves amounts to 7 %, corresponding to a standard deviation of 5 %.

It is difficult to assess the cause of such a wide dis-

* F. D Fielder: *Electric Journal*, 1935, vol. 32, p. 543.

† Fielder's correction factor for the sparkover voltage of a rod-gap using a $1\frac{1}{2}/40$ wave is 2·4 % per grain of water per cubic foot of air different from the standard U.S.A. value of 6·5 grains per cu. ft. As the I.E.C. standard value for humidity is 4·8 grains per cu. ft. the sparkover-voltage correction factor becomes

$$2\cdot4 \times \frac{100}{100 - 2\cdot4\,(6\cdot5 - 4\cdot8)} \text{ per cent}$$

or 2·5 % per grain per cu. ft. different from the standard I.E.C. value of 4·8 grains per cu. ft. This amounts to 1·09 % per gramme of water vapour per cubic metre of air. The factor for a $-1\frac{1}{2}/40$ wave, calculated from Fielder's factor, is 0·83 % per gramme per m³: and for positive and negative 1/5 waves is 0·49 % per gramme per m³

persion of results, especially as most of the curves from the different laboratories are consistent in themselves. It is a common experience in impulse testing to observe a 3 % to 4 % variation between independent deter-

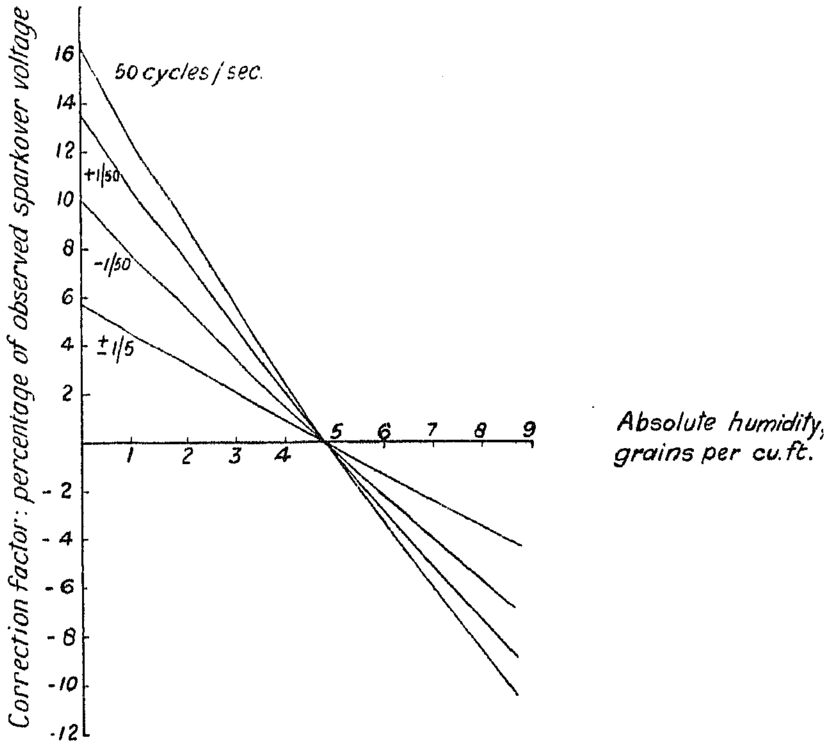

Fig. 1.—Humidity correction curves for rod-gaps.

I.E.C. standard humidity = 4·8 grains per cu. ft.
= 11 grammes per m³
= 64 % relative humidity at 20° C. (68° F.).

minations of the sparkover voltage of a gap taken within short times of one another, but as the curves in Figs. 3–6 represent the mean of many determinations of the same points this inherent fluctuation cannot be wholly responsible for the wide dispersion observed. Many measurements were also taken at different humidities in an attempt to verify Fielder's correction factors, but whereas

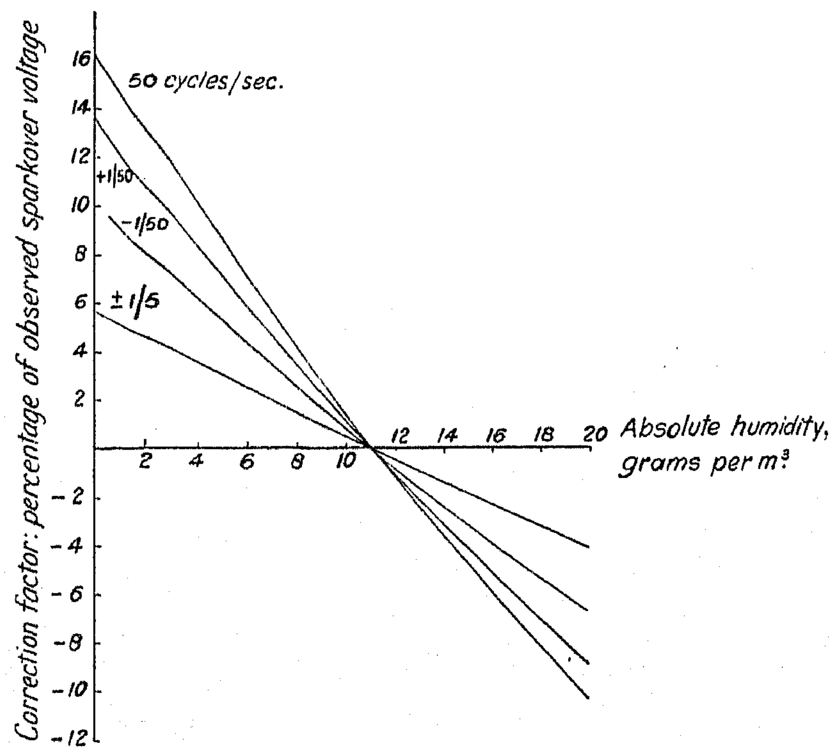

Fig. 1A.—Humidity correction curves for rod-gaps (± 1/50, ± 1/5, and 50-cycle waves).

some results indicate the factors to be high others indicate the opposite. Use of spheres of different diameters may be responsible for some of the error: curve G in Fig. 3, for example, was obtained with 50-cm. diameter spheres up to a rod-gap spacing of 25 cm. and with 150-cm. diameter spheres at rod-gap spacings in excess of 25 cm. The discontinuity of the curve is not so noticeable in Fig. 4 for the negative 1/50 wave. Laboratory F also notes a discontinuity which is not so noticeable in the Figures: calibration of the rod-gap spaced at 25 cm. was effected with a 25-cm. and a 200-cm. sphere-gap; the larger gap gave a 5 % lower calibration. A further cause of the dispersion may be the construction of the rod-gap, but there is only a 3 % change in sparkover voltage of the rod-gap as the clearance of the gap above ground is changed from between 1·5 and 2 to more than 4 times the rod-gap spacing. A further variable is

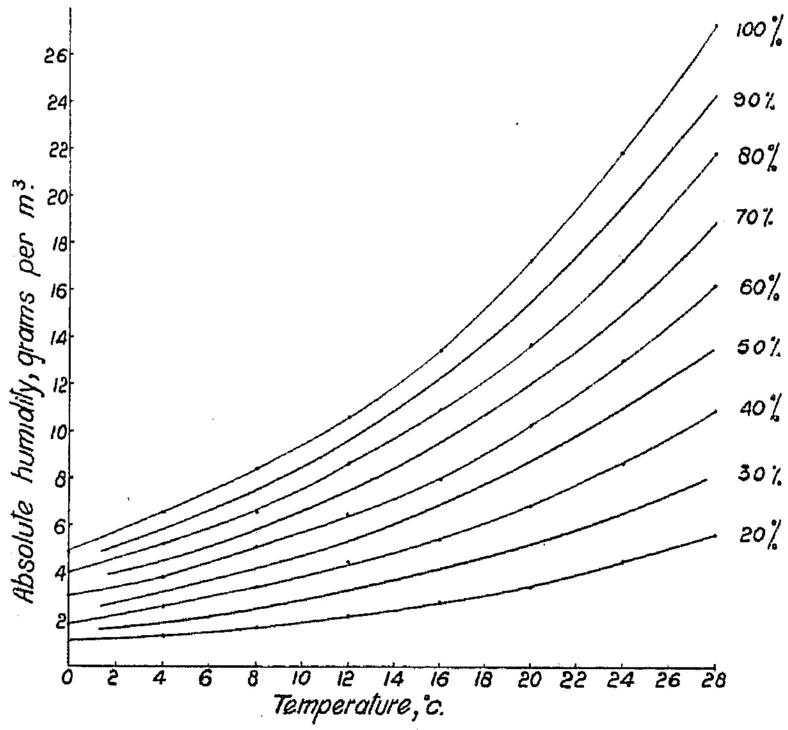

Fig. 2.—Relation between percentage humidity and absolute humidity at various temperatures.*

the discharge capacitance of the generator, though this ought not to affect the results if the wave-shape is checked oscillographically at various rod-gap settings. Variation of wave-shape within the tolerances allowed could alter the results by 5 %. One must conclude that the dispersion of results is due to a combination of the above suggested causes, and accept such dispersion as inherent in impulse-voltage sparkover tests until stricter control of the variables is achieved.

Similar conclusions have recently been reached in the U.S.A.† The curves obtained in five laboratories (Allis Chalmers, General Electric, Locke, Ohio Brass, and Westinghouse) on the calibration of the rod-gap with a positive 1/5 and a positive $1\frac{1}{2}$/40 wave were within ± 5 % of the mean curve, and individual points arrived at in any one laboratory were within ± 5 % of the average curve of that laboratory. As a result of this it was agreed that, when the rod-gap was used as a basis of comparison, the sparkover voltage should be taken from the agreed mean values and considered to be

* See W. WEICKER: *Hescho Mitteilungen*, 1936, vol. 74/5, p. 2357.
† *Edison Electric Institute Bulletin*, August, 1936, p. 351.

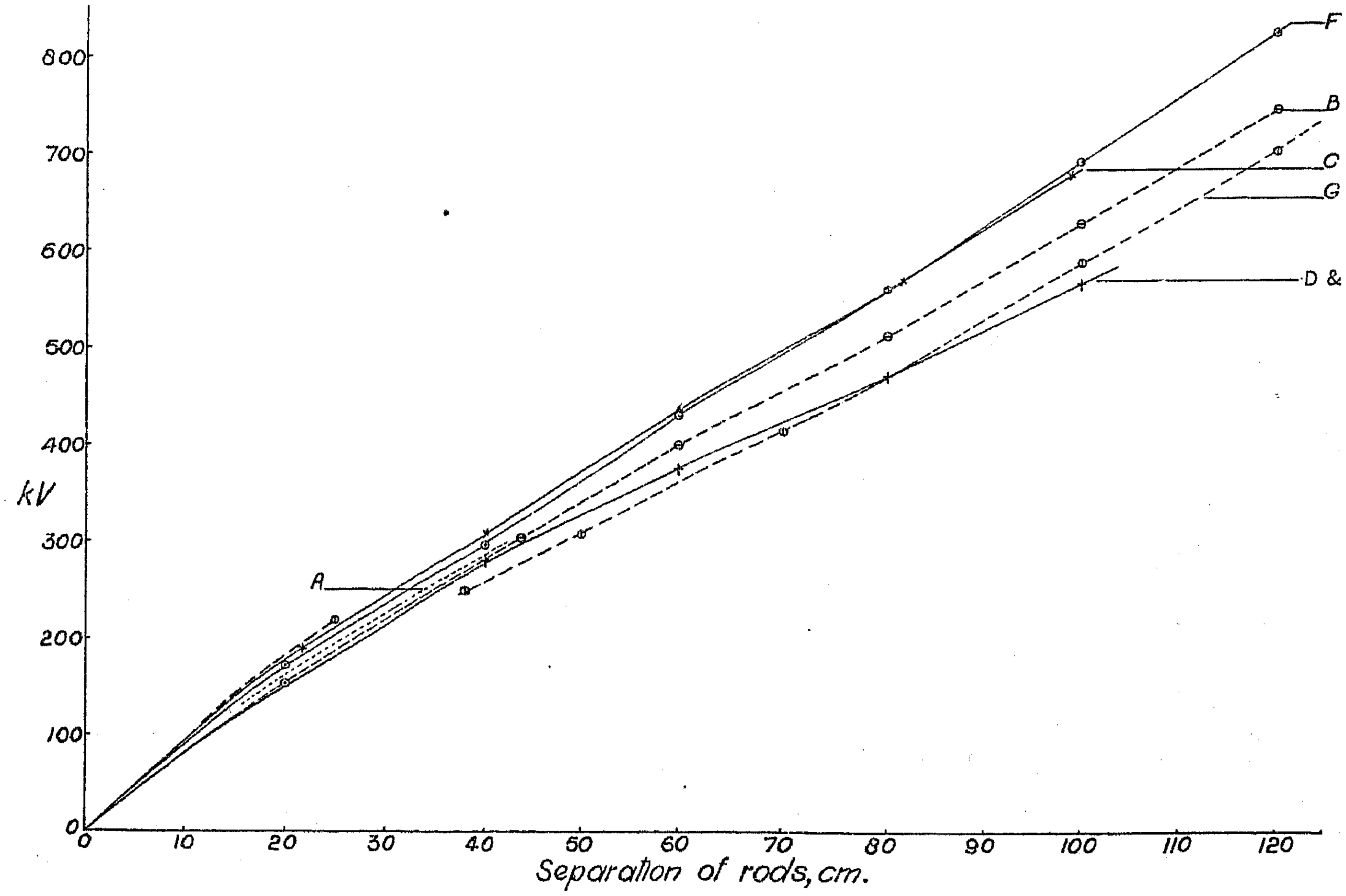

Fig. 3.—Impulse sparkover of rod-gaps (+ 1/50 wave).
Pressure 760 mm. of mercury, temperature 25° C., humidity 4·8 grains per cu. ft. (11 g. per m^3), 90 % sparkover values.

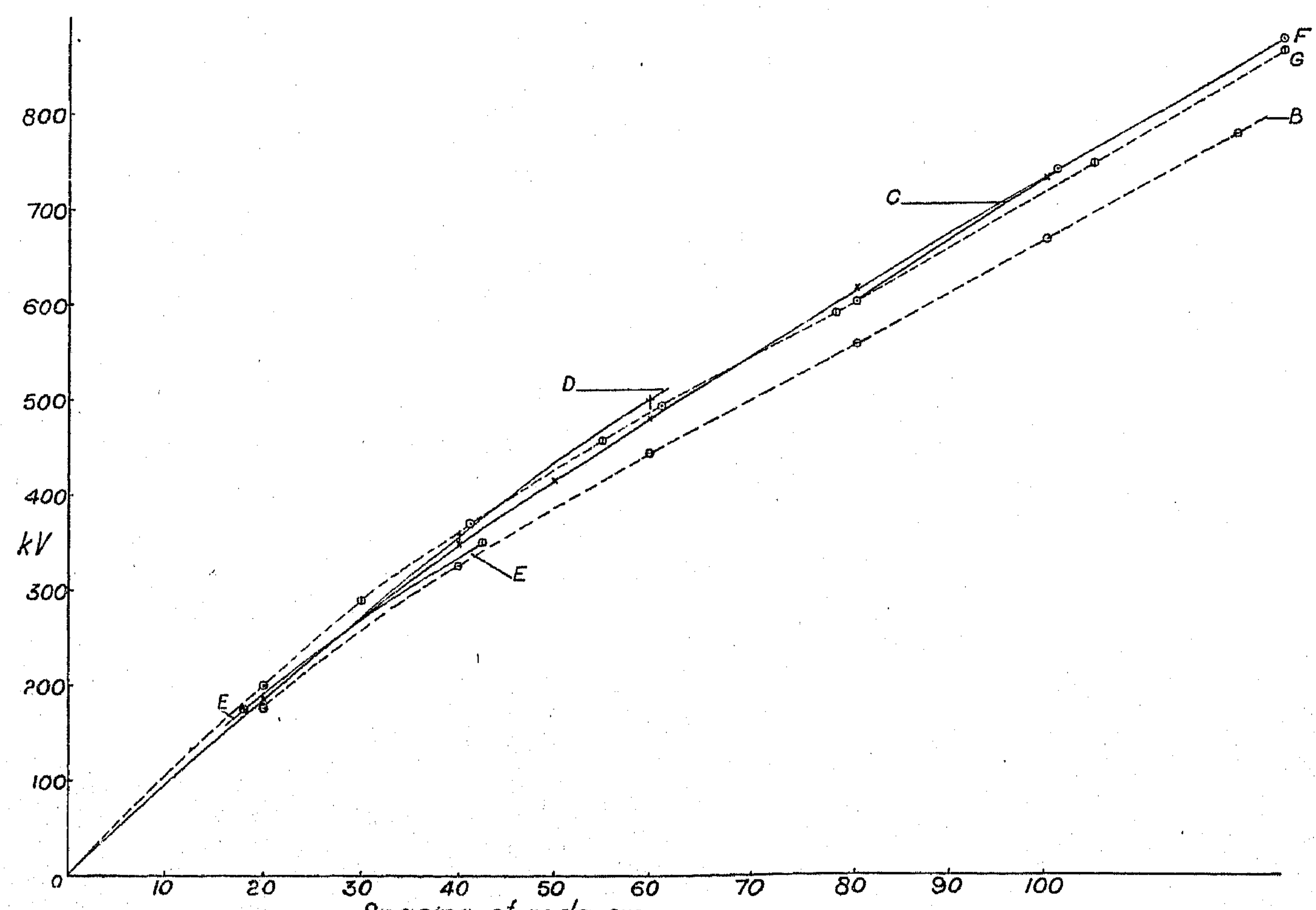

Fig. 4.—Impulse sparkover of rod-gaps (— 1/50 wave).
Pressure 760 mm. of mercury, temperature 25° C., humidity 4·8 grains per cu. ft. (11 g. per m^3), 90 % sparkover values.

A. Not indicated in Fig. 4. In Fig. 3 A refers to curve ....

B. – – – ⊖ – – –	E. ——— ⊕ ———
C. ——— × ———	F. ——— ⊙ ———
D. ——— † ———	G. – – – ⦶ – – –

correct within ± 8 %. The results have been revised and extended very recently (June, 1937) in a report by the Joint Committee on System Insulation Co-ordination of the Edison Electric Institute and the National Electrical Manufacturers Association.* In this revision, humidity factors slightly differing from Fielder's values have been adopted, but the difference does not amount to 2 % in the most extreme instance and the curves given in Figs. 1 and 1A of this paper can be adopted without change.

conclusion being that the difference between 50 % and 90 % sparkover amounted to $1\frac{1}{2}$ % to 5 % for + 1/50 waves and $2\frac{1}{2}$ % to 8 % for − 1/50 waves. A general correction factor of − 4 % was therefore applied to reduce the 90 % sparkover values to values which would probably have been obtained on a 50 % sparkover criterion.

It will be seen from Table 1 that the agreement between the European and American results is generally very good, all curves except the negative 1/5 agreeing

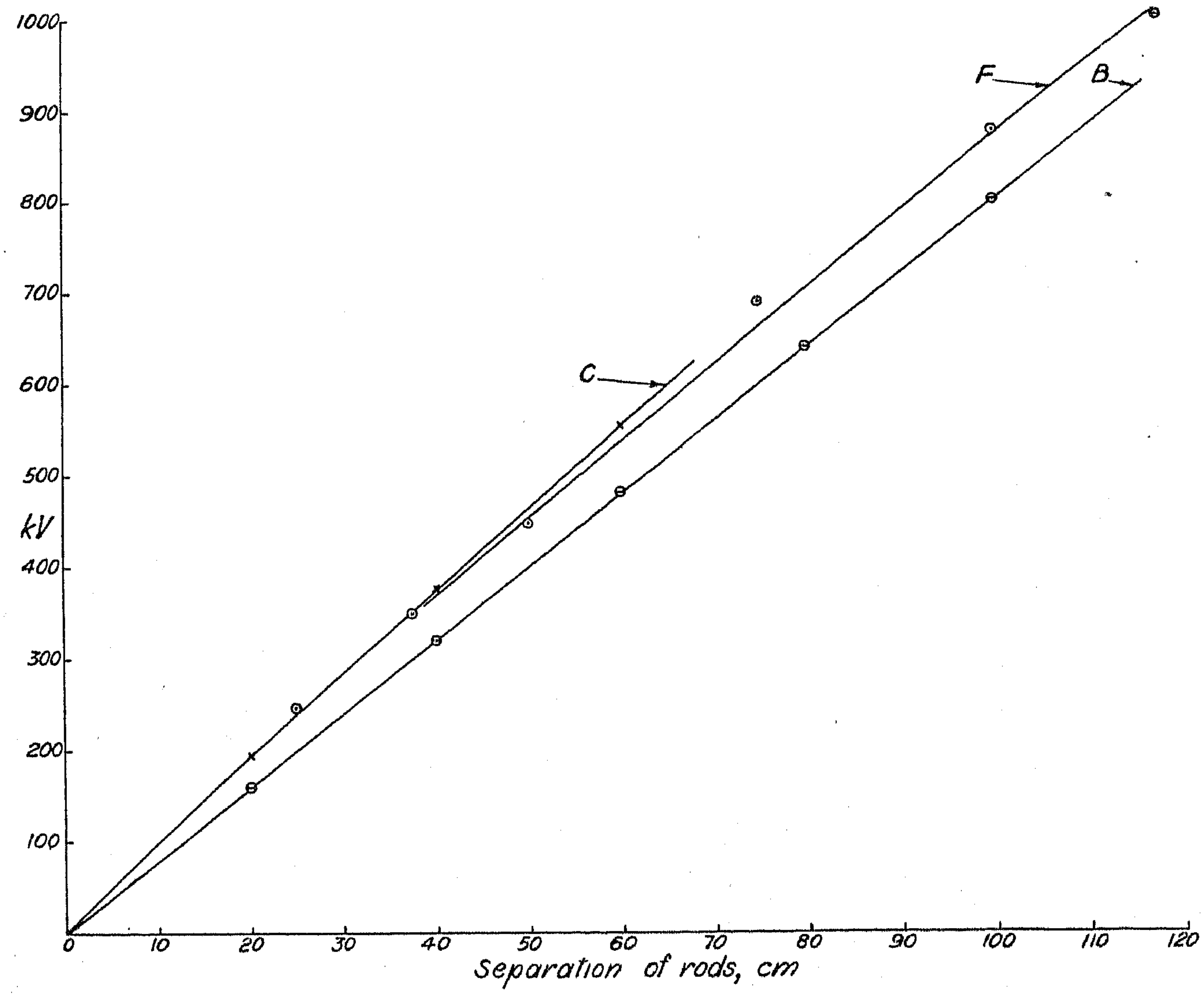

Fig. 5.—Impulse sparkover of rod-gaps (+ 1/5 wave).

Pressure 760 mm. of mercury, temperature 25° C., humidity 4·8 grains per cu. ft. (11 g. per m³), 90 % sparkover values.

B. ——⊖——
C. ——×——
F. ——⊙——

To facilitate comparison between the mean I.E.C. values for rod-gap sparkover and the mean U.S.A. values, the results have been reduced to a common basis and presented in Table 1. In the first place, the U.S.A. values have been corrected to the I.E.C. standards of humidity and temperature. The European results have been corrected to the I.E.C. standard of temperature (20° C.), and to the minimum (50 %) impulse sparkover criterion, which was adopted in place of the 90 % criterion by the I.E.C. Impulse Voltage Sub-Committee in June, 1937, in deference to American usage. This last correction cannot be made with any great certainty; it is known† to be about 4 % to 5 %, and recently‡ was specially investigated in Germany for the I.E.C., the

within 5 %: the negative 1/5 curves differ by up to 10 %. It may be that a rather more rigid definition of wave-shape is required for the 1/5-microsecond wave if these variations are to be reduced in magnitude.

(3) COMPARISON OF IMPULSE-VOLTAGE TESTS ON INSULATORS

It is obvious that of all electrical apparatus the line insulator receives the most severe effects of lightning, and it is reasonable to expect all insulators for outdoor use to remain intact under impulse voltages sufficient to cause sparkover. The determination of the minimum impulse sparkover in the laboratory for the purpose of effecting transmission-line co-ordination should therefore meet with no opposition, and no design of insulator should fracture during such tests. It is known that

* *Electrical Engineering*, 1937, vol. 56, p. 712.
† T. E. Allibone and F. R. Perry: *Journal I.E.E.*, 1936, vol. 78, p. 257.
‡ P. Jacottet: *Elektrotechnische Zeitschrift*, 1937, vol. 23, p. 628.

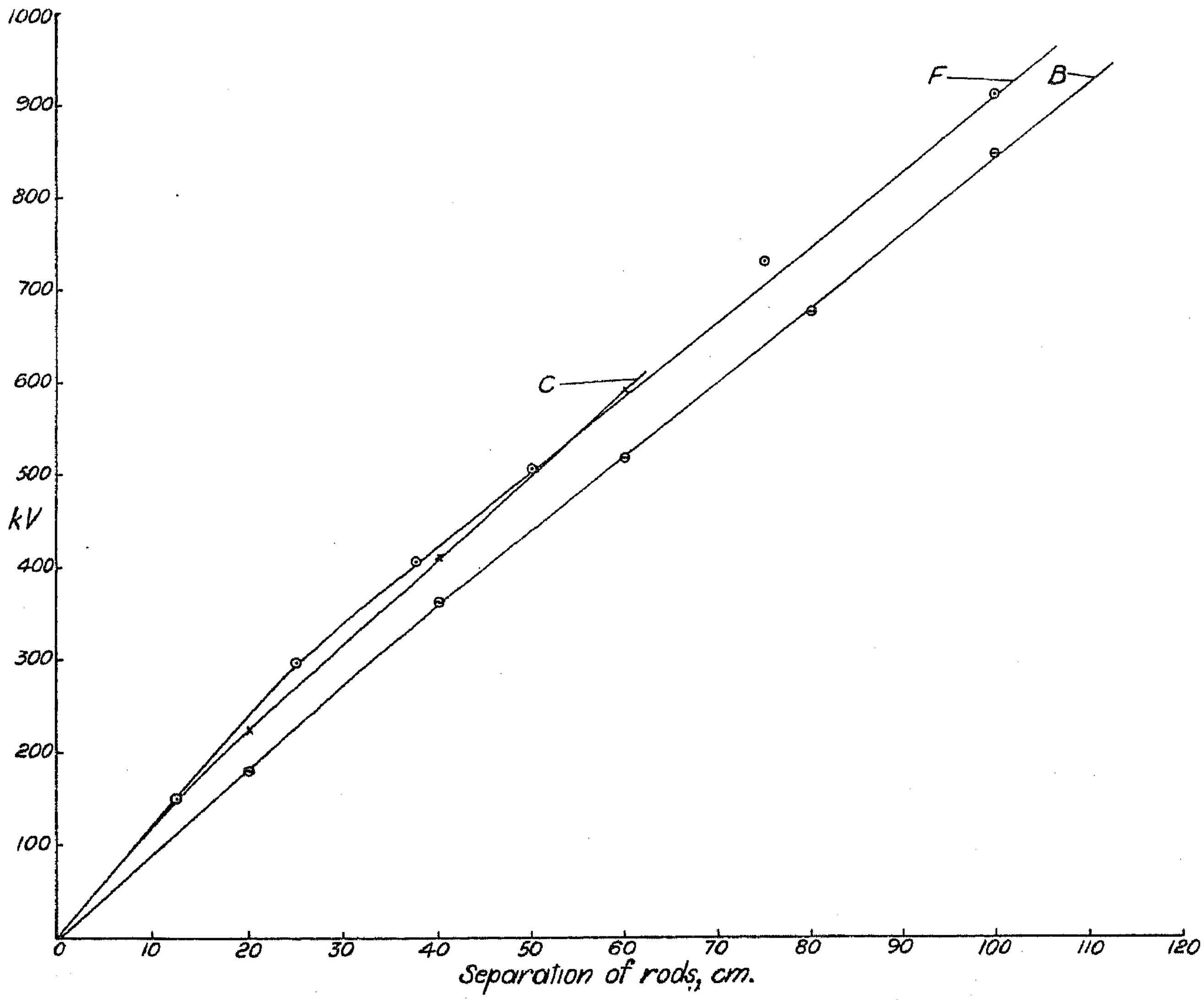

Fig. 6.—Impulse sparkover of rod-gaps (— 1/5 wave).

Pressure 760 mm. of mercury, temperature 25° C., humidity 4·8 grains per cu. ft. (11 g. per m.^{3}), 90 % sparkover values.

B. —⊕—
C. —X—
F. —⊙—

Table 1

IMPULSE SPARKOVER OF ROD-GAPS: COMPARISON OF MEAN RESULTS FROM EIGHT EUROPEAN LABORATORIES WITH MEAN RESULTS FROM FIVE U.S.A. LABORATORIES. RESULTS QUOTED FOR TEMPERATURE 20° C., PRESSURE 760 MM., HUMIDITY 11 G. OF WATER VAPOUR PER CUBIC METRE OF AIR, 50 % SPARKOVER CRITERION*

Rod-gap spacing	+ 1/50 wave		− 1/50 wave		+ 1/5 wave		− 1/5 wave	
	I.E.C.	U.S.A.	I.E.C.	U.S.A.	I.E.C.	U.S.A.	I.E.C.	U.S.A.
cm.	kV	kV	kV	kV	kV	kV	kV	kV
5	56	57	61	60	60	59	66	61
10	90	90	97	99	101	96	111	102
15	129	127	135	136	139	140	155	143
20	160	157	178	175	179	183	208	184
25	195	185	221	217	217	230	257	230
30	226	217	262	259	256	271	301	269
40	279	279	339	333	348	355	392	351
50	334	338	407	396	431	433	475	435
60	393	397	470	463	513	510	557	520
80	511	515	585	590	657	670	701	695
100	629	627	703	715	820	825	855	860
120	752	745	807	850				

* Where laboratories quote an uncertainty range, mean values have been taken.

the impulse ratio for sparkover of line insulators varies over wide limits for different insulators and for different wave-shapes, and the first group of tests recorded in this Section illustrates the variation which exists between pin-type insulators of differing design selected at random. It is clear from such tests that for line co-ordination it is insufficient to calculate impulse sparkover from the power-frequency dry-sparkover value assuming a constant impulse ratio; impulse-type tests are essential to determine the actual sparkover values.

It might be expected, however, that, as many lightning strokes to line or tower cause sparkover at the insulator, voltages well in excess of the minimum sparkover value might appear momentarily across the insulator. It is important to know the general ability of insulators to withstand many impulses at a voltage just sufficient to cause sparkover and at voltages in excess of this value, probably at a voltage sufficient to cause sparkover to take place on the rising front of the wave. To obtain such information the Sub-Committee suggested that tests should be made at the minimum sparkover voltage and at voltages 20 %, 40 %, 60 %, etc., in excess of this value. The results of the tests are given in this Section for pin-type insulators. Details of design are not given, as the sole object of the tests was to guide the I.E.C. in the framing of a specification.

(a) Determination of Minimum (90 %) Impulse Sparkover of Line Insulators

Tests were made in Laboratories A, B, C, and G, on pin-type insulators mounted in the manner prescribed for the power-frequency sparkover test. The impulse ratios for all the tests are given in Table 2. The sizes varied over a wide range, as indicated by the power-frequency dry-sparkover values also given in the Table. The results have not been corrected for humidity, as there is no accepted correction factor for such insulators.

The variation of the impulse ratio depends on the nature of the electrodes, the pin, and the binding wire securing the transmission line. On negative polarity the impulse ratio is higher than on positive polarity owing to the smooth nature of the pin, the earthed electrode. If a point electrode is attached to the pin or the cross-arm near to the lower shed of the insulator, the negative sparkover can be reduced to values as low as the positive sparkover, thus resulting in an insulator giving the same response to surges of both polarities.* Suspension insulators fitted with arcing horns exhibit this property, as may be seen from Table 3. The differences between the impulse ratios determined by the two laboratories are no doubt due to the actual form of the arcing elec-

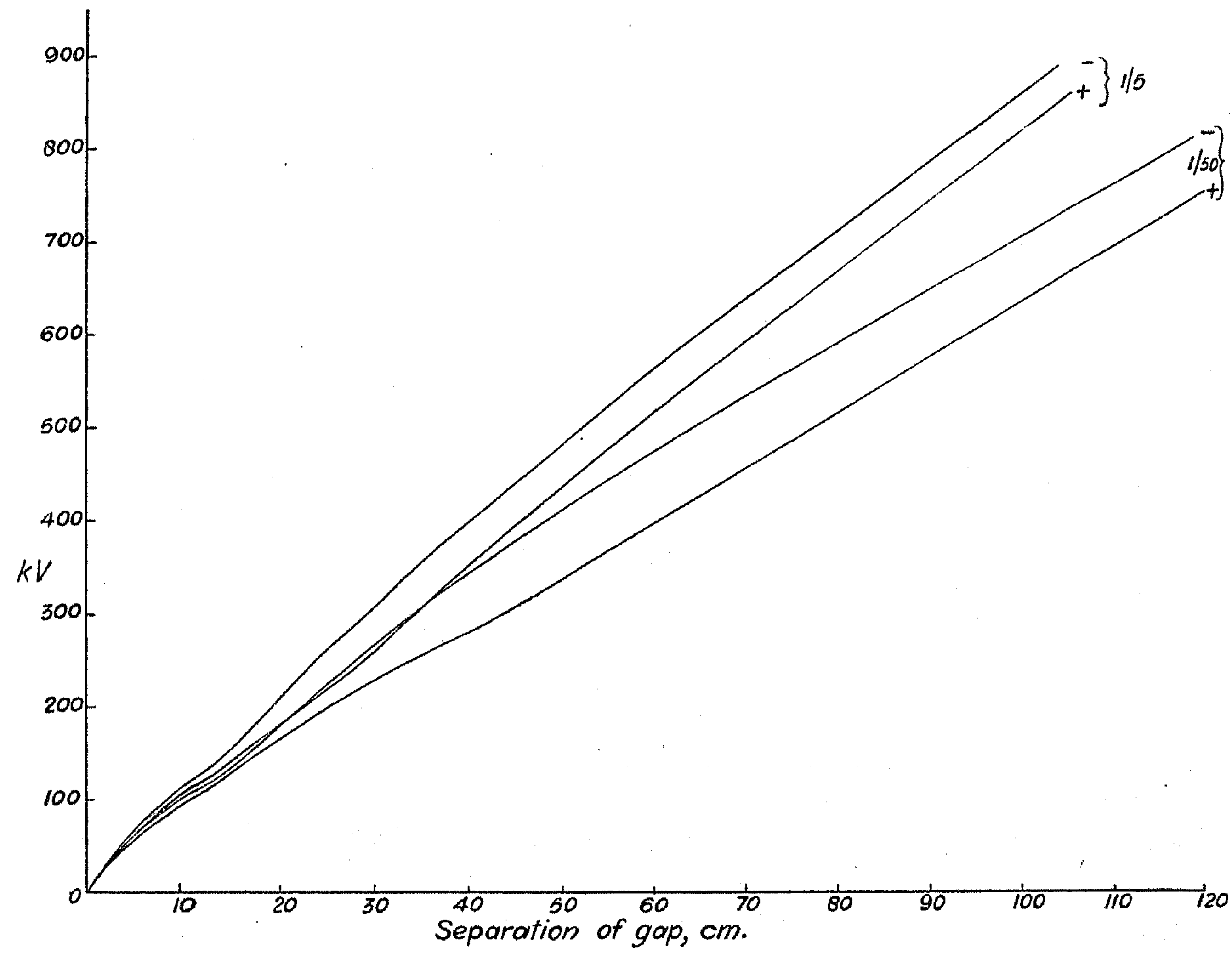

Fig. 7.—Impulse sparkover of rod-gaps (± 1/50 and ± 1/5 waves): average results of eight European laboratories.

Pressure 760 mm. of mercury, temperature 25° C., humidity 11 g. per m^3, sparkover criterion 90 %. Sphere-gaps used at less than radius spacing: I.E.C. curves. Gap mounted at height h given by $1{\cdot}5s < h < 2s$, where s = spacing.

* Further details of this insulator will shortly be published elsewhere.

trodes; at large electrode-spacings the differences disappear.

(b) Determination of General Ability of Insulators to Withstand Impulse Voltages

Tests on insulators were made in Laboratories A, B, C, and G; first, the minimum sparkover voltage was applied 100 times with a + 1/50 wave succeeded by 100 with a − 1/50 wave, 100 with a + 1/5 wave, and 100 with a − 1/5 wave. The voltage was then raised to 1·2 times the minimum value and the sequence

1 failed during the + 1/50 test at 1·4 times minimum sparkover.

1 failed during the − 1/50 test at 1·6 times minimum sparkover.

10 pin-type insulators of varied style were also tested, first with ± 1/50 waves up to minimum sparkover voltage, then with the − 1/50 wave at a voltage sufficient to cause sparkover on the crest of the wave, with the following results:—

1 failed at between 1·2 and 1·4 times the minimum sparkover voltage.

Table 2

Impulse Ratios of Pin-Type Insulators

Laboratory	Power-frequency sparkover (kV eff.)	+ 1/50 wave	− 1/50 wave	+ 1/5 wave	− 1/5 wave
(A) Brussels	77–113	1·17–1·3	1·27–1·46	1·28–1·54	1·36–1·54
(B) Hermsdorf	76–138	1·19–1·40	1·41–1·72	1·30–1·41	1·60–1·68
(C) Manchester	54–168	1·09–1·24	1·30–1·90		
(G) Ludvika	35–102	1·12–1·20	1·65–1·75		

repeated: this was followed by further increments in test voltage, as given below:—

Laboratory A.

10 pin-type insulators were tested in the above sequence. The results were as follows:—

1 failed during the − 1/50 minimum-sparkover test.

3 failed during the − 1/50 test at 1·2 times minimum sparkover.

6 passed the sequence of tests up to 1·2 times minimum sparkover.

2 cap-and-pin insulators passed the sequence of tests up to 1·2 times minimum sparkover.

1 failed at between 1·6 and 1·8 times the minimum sparkover voltage.

8 passed the test at 2 times the minimum sparkover voltage.

Laboratory C.

300 cap-and-pin type suspension insulators of one style were tested with a negative-polarity 1/5 wave at the minimum sparkover voltage; 3 failed. 30 of the same insulators were then tested with 1·5 times the voltage of the first test, and 1 failed. The remainder were then tested with 2·6 times the voltage of the first test, and 1 failed.

Table 3

Impulse Ratios for Suspension Insulators*

Spacing	50-cycle sparkover (kV eff.)		+ 1/50 wave		− 1/50 wave		+ 1/5 wave		− 1/5 wave	
	B	C	B	C	B	C	B	C	B	C
cm.										
20	83	92	1·27	1·46	1·49	1·23	1·36	1·54	1·52	1·46
40	147	162	1·36	1·34	1·58	1·26	1·50	1·56	1·77	1·62
60	211	230	1·36	1·29	1·53	1·29	1·60	1·68	1·73	1·72
80	280	300	1·34	1·27	1·44	1·32	1·62	1·73	1·72	1·78
100	348	366	1·32	1·26	1·38	1·34	1·62		1·68	

* B = Hermsdorf, C = Manchester.

Laboratory B.

5 pin-type insulators of one style were tested in the above sequence. The results were as follows:—

2 failed during the − 1/50 test at 1·2 times minimum sparkover.

1 failed during the − 1/5 test at 1·2 times minimum sparkover.

Laboratory G.

30 pin-type insulators of 6 different styles were tested according to the following schedule: groups of 20 impulses each were applied having crest values of 2, 4, and 8 times the peak value V_{max} of the power-frequency dry-sparkover voltage. The tests were made first with positive, then with negative impulses. It was shown

that sparkover took place near the crest of the wave when an impulse of $2V_{max}$ was applied, and with the higher test-voltages sparkover took place on the wave-front. The results for the 30 insulators were as follows:—

1 failed during the $-2V_{max}$ test,
4 failed during the $-4V_{max}$ test,
4 failed during the $+8V_{max}$ test,
4 failed during the $-8V_{max}$ test.

The other 17 insulators withstood all the tests, thus withstanding sparkover on a wave-front having a rate of rise of voltage as high as 800 kV per microsecond.

A further set of tests made in Laboratory C give

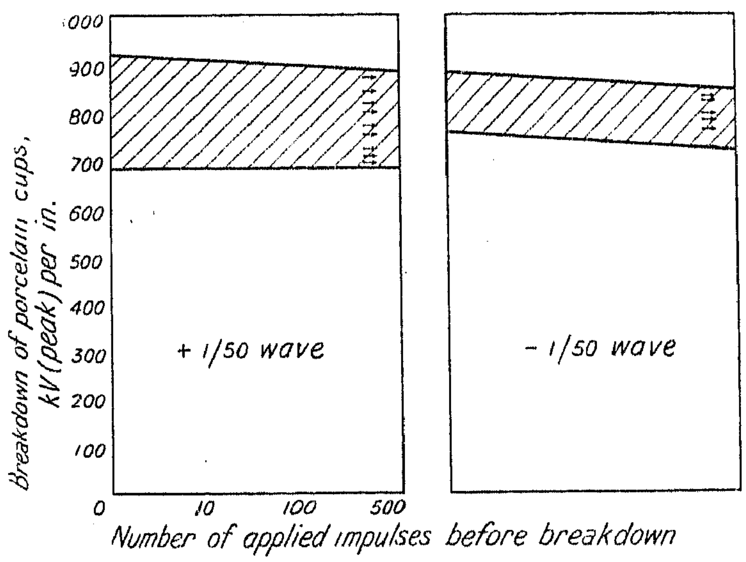

Fig. 8

additional information on the subject under review. The fatigue of porcelain under impulse voltages was examined using the ± 1/50 and ± 1/5 waves and also the 1/50 wave chopped on the crest by a spark-gap, designated ± 1/0 waves. To eliminate edge effects, and so to obtain a true value for the puncture voltage of porcelain, specially-shaped porcelain test cups were used, hollowed internally to a 1-in. radius and having a flat base, the minimum thickness at the base of the cup being 0·15 in. The cups were completely fired but were unglazed: the inside was coated with graphite and partly filled with mercury, and the cups stood on a trough of mercury totally immersed in oil.

The impulse breakdown voltage of the cups for any one wave-shape was first determined approximately: a voltage lower than this was then applied to each of 10 cups in turn, impulses up to 500 in number being applied to each cup or until such time as the porcelain fractured. The number of impulses was recorded as shown in Fig. 8; if the cup did not break down the result is indicated on the Figure by an arrow on the "500" line. To a fresh series of 10 cups, impulses were applied at 5 % in excess of the former applied voltage until breakdown occurred or until 500 impulses had been applied. The same procedure was followed at successively higher voltages on fresh specimens until breakdown occurred consistently on the first application of the voltage. Thus Fig. 8 is a measure of the extent to which the material is fatigued by many applications of stress. It will be seen that almost no fatigue is apparent over the range observed, so that little or no damage is likely to be done to the porcelain of an insulator during the testing of the insulator under impulse voltages at voltages lower than the puncture voltage. The values in Fig. 8 show a wide dispersion and are therefore enclosed in boundary lines to indicate the extreme values of the results. As all the wave-shapes gave similar results, only one set has been shown in graphical form. The impulse puncture voltages for the porcelain test-cups are given in Table 4, and the power-frequency and constant-potential breakdown values are also given, for normal temperature (18°–23° C.). It will be further observed that the wave-shape of the applied impulse does not appreciably affect the puncture voltage.

From the tests detailed in this Section one can conclude that insulators which have successfully withstood power-frequency tests may sometimes be fractured by impulse voltages at or above the value corresponding to the minimum impulse sparkover voltage. Whether the insulator fails under impulse voltages probably depends on the design: some of the types investigated appear to withstand very large over-voltages, although no rates of rise of voltage in excess of 800 kV per microsecond have been employed. Negative-polarity impulses cause more fractures than those of positive polarity, but since the true puncture voltage of porcelain appears to be independent of polarity the observed effect may be due mainly to the fact that the insulators are all pin-type insulators, for which negative sparkover is in excess of positive sparkover.

Fatigue does not appear to play an important part in the process of insulator failure: certainly 100 applications of voltage very near to the puncture voltage do

Table 4

Breakdown Strength of Porcelain Test Cups, in kV per inch

50-cycle breakdown (peak value)	560, standard deviation 30 %	
Positive constant potential	731, standard deviation 17 %	
Negative constant potential	668, standard deviation 25 %	
Positive 1/50 impulse	680–940, mean 810	Mean impulse ratio for puncture of porcelain, 1·5
Negative 1/50 impulse	750–890, mean 820	
Positive 1/5 impulse	780–880, mean 830	
Negative 1/5 impulse	740–900, mean 820	
Chopped + 1/0 impulse	760–980, mean 870	
Chopped − 1/0 impulse	760–970, mean 860	

not cause a noticeable lowering of the impulse breakdown value of insulators.

(4) CONCLUSIONS

The international comparison of impulse-voltage testing has been most valuable in showing that all investigators are encountering the same sort of problems and that no laboratory can claim the high order of accuracy for impulse-voltage testing that is possible for power-frequency testing. As a result of this comparison attention will no doubt be given by many to the fine points of technique. A thorough examination of the sphere-gap calibration under impulse voltages is first required. At present, tests involving the measurement of sparkover must be allowed a considerable latitude, of the order of $\pm$ 8 %, so that it is clear that a scheme for the co-ordination of line and station insulation cannot be based on fine margins between the impulse sparkover of the component parts.

There would appear to be good reasons for advocating the introduction by the I.E.C. of impulse-voltage type tests for line insulators to eliminate those designs which are punctured at relatively low impulse voltages: at least it would be reasonable to expect all line insulators to be capable of withstanding a voltage somewhat in excess of the minimum impulse sparkover voltage, most probably a voltage sufficient to cause breakdown on the crest or front of the wave. For pin-type insulators, which are not generally employed to insulate lines of a service voltage in excess of 33 kV, such a test would only result in a rate of rise of voltage of less than 1 000 kV per microsecond, and from data accumulated on lines it is known that this rate of rise of voltage may be exceeded.

The author* wishes to express his thanks to his colleagues on the I.E.C. Sub-Committee on Impulse Voltages, for the use of data they have presented to the Sub-Committee; also to Mr. D. B. McKenzie, who assisted with the tests on insulators reported under the heading "Laboratory C"; also to Messrs. Taylor, Tunnicliff and Co., for the supply of porcelains on which the author's tests were made; and finally to Dr. A. P. M. Fleming, C.B.E., Director and Manager of the Research and Education Departments, Metropolitan-Vickers Electrical Co., Ltd., for permission to publish this paper.

* The author is Secretary of the Sub-Committee on Impulse Voltages, International Electrotechnical Commission.

THERMAL FLUCTUATIONS IN COMPLEX NETWORKS.*

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(*Paper first received* 16*th March and in final form* 24*th July*, 1937.)

SUMMARY

This paper is concerned with the thermal fluctuations generated in networks containing reactance as well as resistance. Earlier work is reviewed, and it emerges that Moullin and Ellis were unable to interpret Nyquist's equation for a network at uniform temperature by their method of representation. An alternative method is suggested in which each element of resistance is replaced by a fluctuation generator in series with the element of resistance. The fluctuation voltage appearing between any two points in a linear network with any temperature distribution is then evaluated. This general expression is shown to be in agreement with Nyquist's result if the temperature is uniform. It is also shown that the relevant values of resistance in these formulae are the equivalent power-loss resistances and not the metallic resistances.

There follows a description of experimental tests which are regarded as satisfactory verification of the method of representation adopted and of the values of resistance used.

The noise/signal ratio existing between any two points in the generalized network is then discussed, and is shown to be incapable of exceeding the value obtaining in the arm in which the signal is introduced. General recommendations for optimum noise/signal ratio are given.

A few special cases are then considered. It is shown that in radio reception a resonant circuit is preferable to a band-pass filter as a coupling between aerial and amplifier. In the former case an analysis of the optimum coupling between aerial and circuit is given which takes account of the fluctuations generated in the amplifier itself. A simple practical method of obtaining the optimum conditions is outlined.

Fluctuations in long cables are briefly discussed. It is shown that temperature conditions in the vicinity of the receiving end only need be considered. The use of transformers or resonant circuits to couple the cable to an amplifier is governed by the same recommendations as for aerial-amplifier coupling.

(1) INTRODUCTION

It is well known that there exists across the extremities of a resistor a fluctuation voltage which is dependent on the absolute temperature of the resistor. Such fluctuations have been ascribed to the thermal agitation of the electrons contained in the resistor, and have been the subject of considerable investigation, both analytical and experimental.

Thus Johnson,† Nyquist,‡ and Moullin and Ellis,§ have all shown that the mean-square thermal agitation voltage developed across a resistance R can be expressed in the form

$$|v|^2 = 4Rk\tau df \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $|v|^2$ is the mean-square value of those harmonic components of the total fluctuation voltage which have frequencies within the range df, k is Boltzmann's gas constant, and τ is the absolute temperature of the resistance.

Johnson has tested this expression by deducing a value for k from observations of the fluctuation voltage appearing across metallic and electrolytic resistors, Moullin and Ellis† made a similar series of measurements of k using a highly refined technique by which the probable error was reduced to about 1 per cent, but confined their attention to metallic resistances. In all cases good agreement with the accepted value was found.

Nyquist extended his analysis to the general case of fluctuations in a network of impedances containing reactive as well as resistive components. He showed that if $(r + jx)$ is the impedance between any two points in the network at the frequency f, then the mean-square

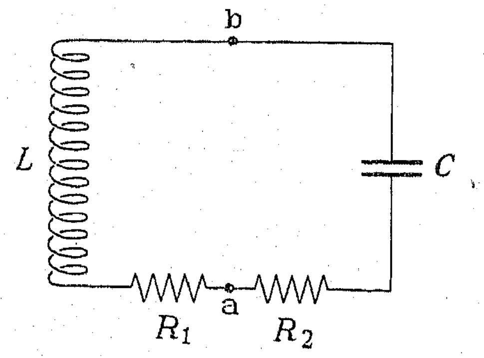

Fig. 1

value of the fluctuation voltage between the limits f and $(f + df)$ is given by the equation

$$|v|^2 = 4rk\tau df \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

So far as the author is aware this expression has not been tested experimentally.

Moullin and Ellis‡ have stated that they cannot understand Nyquist's proof and have given an example in which, according to their interpretation of thermal fluctuations, equation (1a) is at fault. They considered the circuit shown in Fig. 1, which represents a resonant circuit having resistances R_1 and R_2 in series with the inductance and capacitance arms respectively. They calculated the fluctuation voltage appearing between the points a and b by their own method and also by means of Nyquist's equation. The two methods agreed only when R_2 was zero.

A knowledge of the thermal fluctuations to be antici-

* The earlier portions of the paper were the result of research work carried out during the author's tenure of the Ferranti Scholarship.

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† See Bibliography, (1). ‡ *Ibid.*, (2). § *Ibid.*, (3).

† See Bibliography, (4). ‡ *Ibid.* (3).

pated in complex networks such as filter circuits is of considerable importance in many branches of communication engineering, and the present paper is devoted to a discussion of these conflicting views and to the provision of a general formula for estimating the thermal fluctuations generated in any network. The concluding sections discuss the application of the formula to practical cases.

(2) ANALYTICAL DISCUSSION

Experimental measurements have been confined almost entirely to the potential difference developed by thermal agitation disturbances across the extremities of a resistor, comparison with analysis being made by means of equation (1). Yet it appears from the Moullin–Ellis derivation of equation (1) that this equation refers rather to the effective e.m.f. of thermal agitation acting round the complete LCR circuit which, inevitably, is associated with the resistance. Since the value of the e.m.f. depends only on the resistance, and not on the inductance and capacitance, it is usual to associate thermal agitation voltages with the resistance; whether such association has any physical significance remains in doubt. It appears probable, however, from the form of the equation, that the thermal agitation disturbances in any circuit might be most conveniently evaluated by asso-

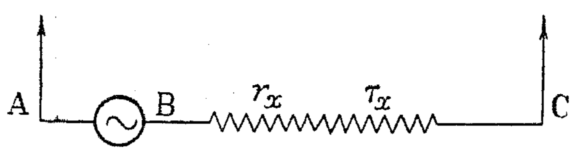

Fig. 2

ciating a hypothetical fluctuation generator with every element of resistance in the circuit; the e.m.f. of the fluctuation generator being given by equation (1) and being supposed concentrated, for convenience.

Under such circumstances, every element of resistance in the circuit would be replaced by the combination shown in Fig. 2. The fluctuation generator is supposed such that it maintains a mean-square p.d. given by

$$|v|^2 = 4r_x k\tau_x df$$

between the points A and B, where τ_x is the absolute temperature of the typical resistance r_x. Since the generator is merely a convenient representation of a distributed effective e.m.f., it must be supposed that A and C are the only points available for external connection, and hence that the generator cannot be isolated from its associated resistance r_x.

It may be noted that rigorous physical support for this representation is not attempted. It is put forward as a convenient analytical representation whose ultimate justification must rest upon experimental evidence. That it is valid for sensibly isolated resistances is evident from results already quoted; its validity in more general circuits will be established later in the present paper.

With representation as defined above, it is shown in Appendix 1 that the fluctuation voltage appearing between any two points A and A′ in a network of linear impedances is given by the equation

$$|v|^2 = Z_{AA'}^2 4kdf \sum \frac{r_x\tau_x}{Z_{Ax}^2} \quad . \quad . \quad . \quad (2)$$

where $|v|^2$ = mean-square fluctuation voltage within the frequency range df; Z_{Ax} = modulus of the transfer impedance from the hypothetical generator in series with the typical resistance r_x to a short-circuit across the points A, A′; $Z_{AA'}$ = modulus of the network impedance from A to A′; τ_x = absolute temperature of the typical resistance r_x.

Also, if the impedance from A to A′ is $(r + jx)$, then it is shown in Appendix 2 that

$$r = Z_{AA'}^2 \sum \frac{r_x}{Z_{Ax}^2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

It follows from equations (2) and (3) that, if the network is at the uniform temperature τ, then

$$|v|^2 = 4rk\tau df$$

the result which was obtained by Nyquist [equation (1a)].

Nyquist's result for a general network is therefore consistent with the accepted expression relating to simple resistances, provided that that expression is interpreted as has been described above, and provided also that the network is composed only of linear impedances. This last proviso was not apparent from Nyquist's proof. Accordingly, Llewellyn* applied Nyquist's result to a network containing a thermionic valve, and put forward the hypothesis that thermal fluctuations were generated in the anode-slope resistance of the valve. This hypothesis has since been disproved experimentally,† thus supporting the view that equation (1a) refers only to linear networks.

The integrations performed in the derivation of Moullin and Ellis were possible only when the resistance was regarded as independent of frequency. Accordingly, they were unable to decide from their analysis whether the relevant value of resistance in the above formulae was the metallic resistance or the equivalent power-loss resistance. The expression for r obtained in Appendix 2 is the equivalent power-loss resistance. It follows that an experimental check of equation (1a) or (2) will not only verify the validity of the method of representation adopted, but will also determine which is the relevant value of the resistance in those formulae. An exhaustive experimental investigation was therefore undertaken and is described in the succeeding sections.

(3) EXPERIMENTAL VERIFICATION

The apparatus used in making the measurements about to be described was similar to that mentioned in previous papers relating to shot effect.‡ A 6-stage amplifier was used which employed resistance-capacitance coupling. Each stage was separately screened, and the amplifier was further subdivided into three sections by further screening boxes which enclosed the necessary battery supplies. An attenuator with logarithmic grading was included between the second and third stages of amplification, and a resonant filter having adjustable parameters between the fourth and fifth stages. The calibration system was similar to that used by Moullin and Ellis, and is fully described in their paper.§ The amplifier was capable of giving a maximum voltage amplification of about 10^8 and was completely stable.

* See Bibliography, (9).
† *Ibid.*, (5), (6).
‡ *Ibid.*
§ *Ibid.*, (4).

(4) MEASUREMENTS WITH METALLIC RESISTANCES

The first series of measurements was made with a non-inductive wire-wound resistor. They were made in order to check the performance of the amplifier and to permit the use of the resistor for calibration purposes in later experiments. The resistor used had a value of 10 070 ohms and was tapped at 5 485 and 1 850 ohms. It had been used successfully in the measurement of shot voltages up to frequencies of about 400 kc.* Such high frequencies are not approached in the present research.

The circuit used in these tests is shown in Fig. 3, the harmonic calibration voltage being introduced at S. One end of S was connected to earth as shown, and all other apparatus was earthed at this point. Such earth connection has been found to reduce spurious input voltages to a minimum.

The deflection due to shot effect in the amplifier was first observed by connecting the amplifier input terminal to earth. The resistance was then introduced and the added deflection due to thermal fluctuations noted. A sinusoidal voltage of suitable magnitude and frequency was next introduced at S and the further increase in deflection was observed. The ratio of these last two increments of deflection gives a measure of the effective

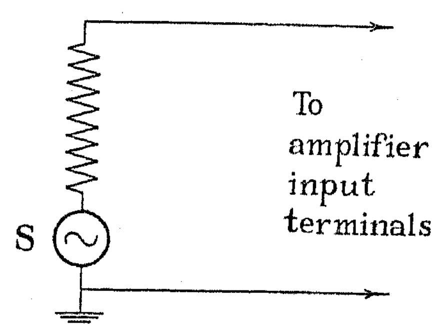

Fig. 3

series e.m.f. of thermal agitation which is independent of any unavoidable capacitance shunt imposed by the amplifier. The experimental correction for this capacitance adopted by Moullin and Ellis is therefore unnecessary. The frequency/response curve of the amplifier was delineated and applied to the formulae in a manner which has been fully described elsewhere.†

The results were used to determine a value for Boltzmann's constant, k, and were expressed in terms of the ratio k'/k, k' being the value determined by experiment. In all, 28 values of k' were obtained using filters with resonant frequencies spread over the audio-frequency band. The mean value of k'/k was $1 \cdot 007$, individual results varying between $0 \cdot 95$ and $1 \cdot 06$.

These results were felt to be a sufficient check of the accuracy of measurement obtained with the apparatus, and to justify the use of the resistance for calibration purposes. Experiment also showed that the input impedance of the amplifier was high enough to be neglected.

(5) THERMAL FLUCTUATIONS IN RESONANT CIRCUITS

It has been stated in Section (1) that Moullin and Ellis were unable to agree with Nyquist's prediction of the thermal fluctuations generated in a resonant circuit which included resistance in the condenser arm. The circuit shown in Fig. 4 was therefore set up to differentiate between the alternative formulae. The resistance could be included in either the inductance or the capacitance arm, or could be equally divided between the two arms, by connecting one of the points a, b, c, to earth.

According to Nyquist, the agitation voltage should be given in all circumstances by equation (1a). The values of r (denoted by r_a, r_b, and r_c) relevant to connection being made to a, b, or c, were therefore calculated. For simplicity it was assumed that the equivalent loss resistance of the coil and condenser, a series resistance of 104 ohms at resonance, was constant and added to the inserted metallic resistance of 896 ohms, which was accordingly assumed to have a value of 1 000 ohms and to be centre-tapped. With these assumptions the calculated values of r_a, r_b, and r_c, are shown by the dotted curves of Fig. 5.

A sharply tuned resonant filter of adjustable resonant frequency was incorporated in the amplifier in order to obtain a measure of r_a, r_b, and r_c at various frequencies by fluctuation measurements. Values were obtained by

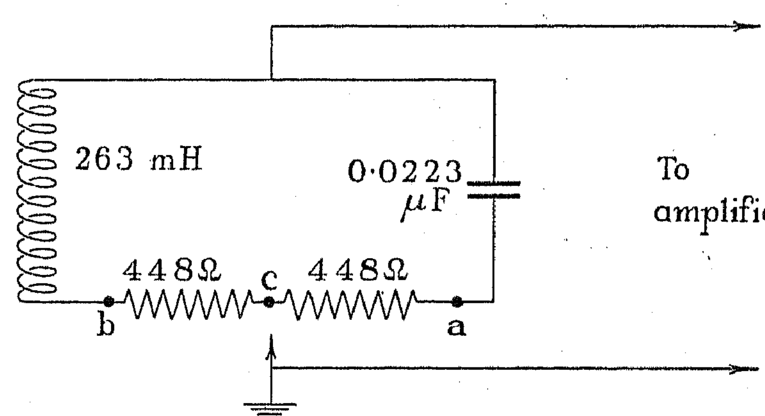

Fig. 4

comparing the output deflection due to the resonant circuit with that obtained from the calibrating resistance. The results are shown by the plotted points in Fig. 5, through which mean lines have been drawn.

Experiment is found to be in good agreement with prediction except in the vicinity of resonance, where the experimental values are about 8 % low. This discrepancy is ascribed to the finite band width of the amplifier response curve; for it can be shown that in the region of the resonant frequency experimental results are low on that account by a fractional amount approximately equal to the ratio of the filter power factor to the test-circuit power factor. In these experiments the ratio was 6 %. The maintained discrepancies found on the skirts of the curves can be explained in terms of the residual losses in the coil and condenser. The average ratio of the predicted to the experimental values of r_a, r_b, and r_c, for all experimental points on the figure are $1 \cdot 02$, $0 \cdot 96$, and $1 \cdot 005$ respectively. Thus experiment supports Nyquist's equation. The values predicted by the equation of Moullin and Ellis* lie very close to the curve of r_a, differing by a maximum of + 8 % at the resonant frequency. Experiment therefore fails to confirm their equation.

* See Bibliography, (7).

† *Ibid.*, (3), (4), (5), (6).

* See Bibliography, (3), p. 331.

(6) FLUCTUATIONS IN BAND-PASS FILTERS

The next series of experiments was made with a band-pass filter. The circuit of the filter used is shown in Fig. 6. The two branches of the filter were carefully matched. The calculation of the equivalent series resistance of such a filter is laborious, and measured values were therefore used. The "three voltmeter" method was adopted, the arrangement of the connections being such that the amplifier could be connected across the filter, across a known resistance in series with the filter, or across a sinusoidal source supplying current to the series combination of filter and resistance. The source was of adjustable frequency and yielded deflections great compared with those due to fluctuation voltages. The equivalent series resistance of the filter was deduced by drawing the vector triangle corresponding to the square roots of the three deflections obtained. The values obtained from these measurements are shown by the dotted curve of Fig. 7.

The fluctuation voltage appearing between the points a and b (Fig. 6) was then measured and expressed as before in terms of the metallic resistance required to give an equal deflection. The results are shown by the plotted points in Fig. 7. Agreement between the two methods of measurement is good except that the fluctuation measurements do not show the sharply-defined peaks and trough shown by the alternative method. This discrepancy is again ascribed to the finite band width to which the amplifier responds, and as before is of the type and order to be expected.

The experiments so far described relate to circuits in which the bulk of the losses could be ascribed to metallic

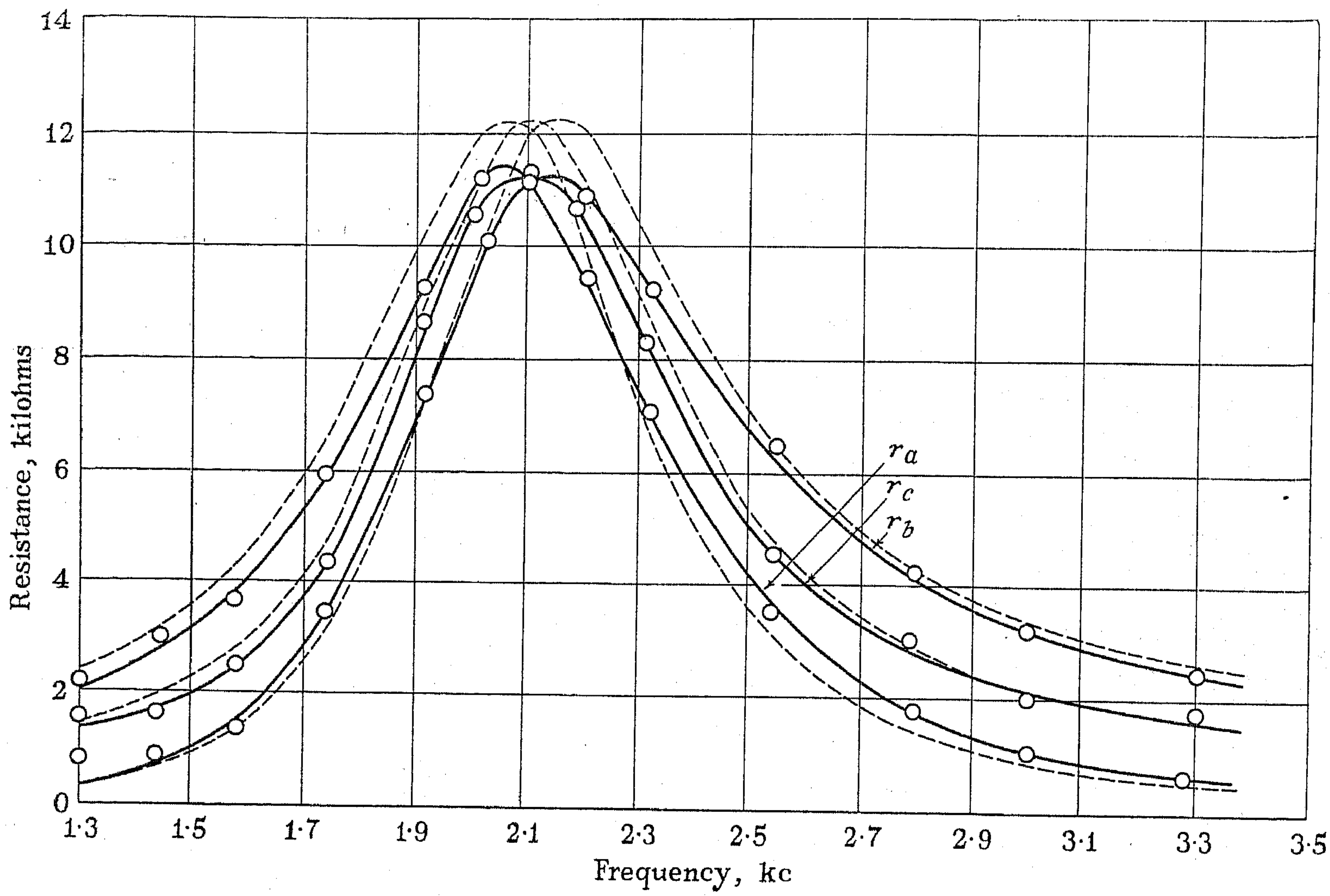

Fig. 5.—Equivalent resistance of resonant circuit as a function of frequency and disposition of resistance. Dotted curves show calculated values; plotted points have been deduced from fluctuation measurements.

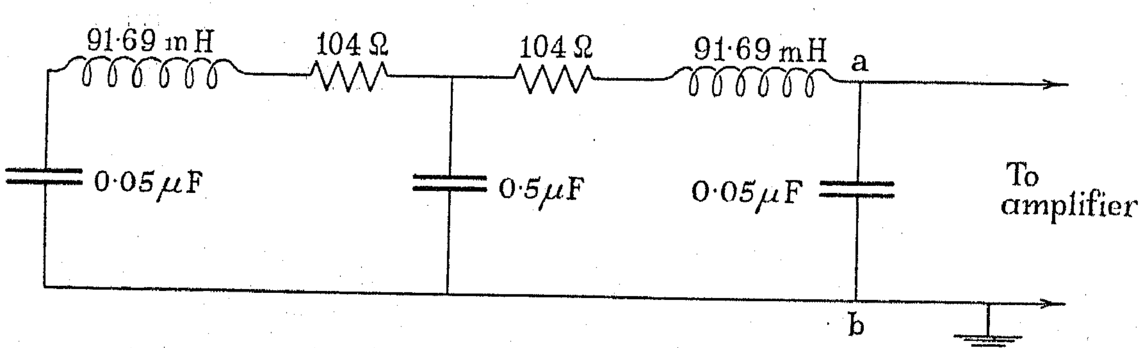

Fig. 6

resistances. In many practical circuits losses due to eddy currents, hysteresis, or poor dielectrics, are predominant. The next section describes some measurements made under such circumstances.

corresponded to a total effective series resistance of about 2 000 ohms. In the absence of the added resistance the band width was not sufficiently greater than that of the filter incorporated in the amplifier.

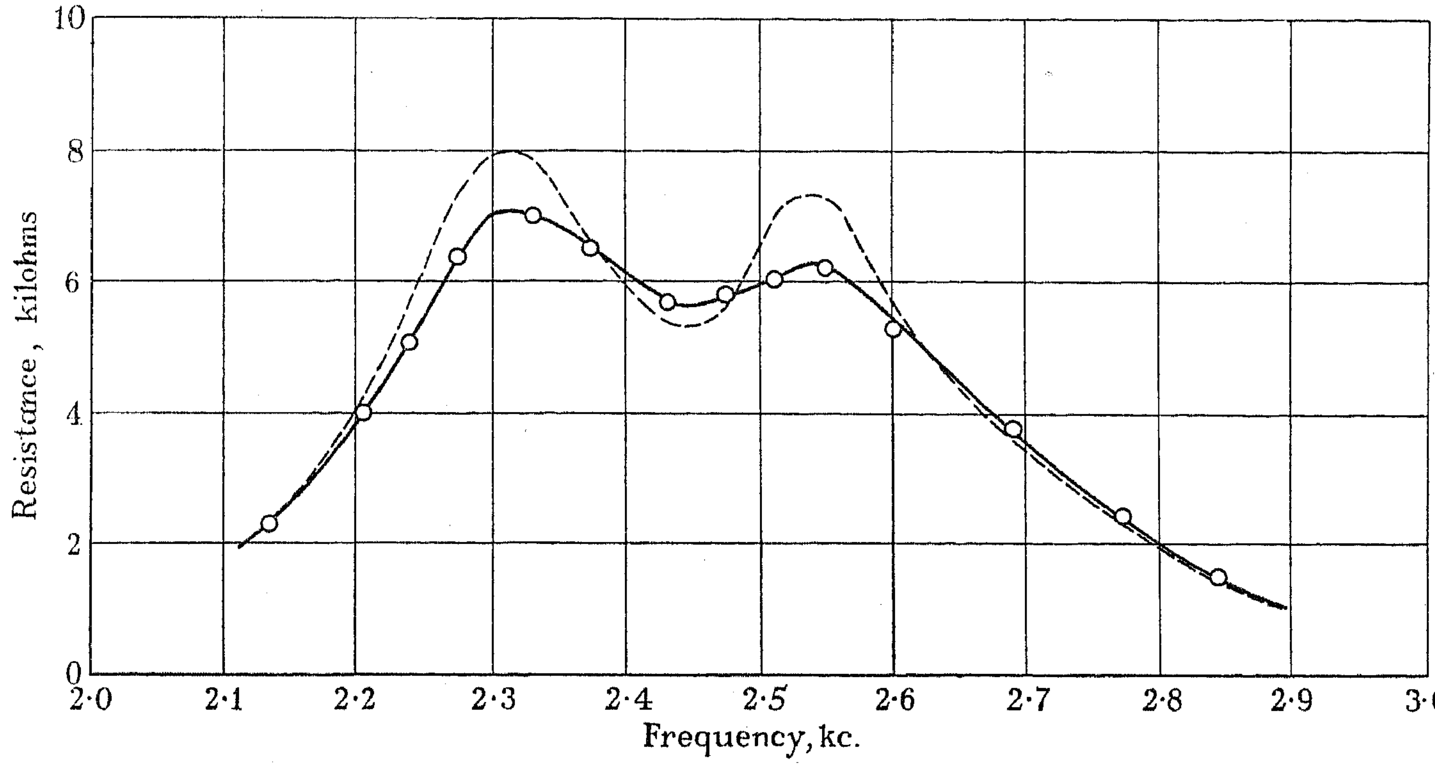

Fig. 7.—Equivalent resistance of a band-pass filter as a function of frequency. Plotted points have been deduced from fluctuation measurements; dotted lines show values obtained by the three-voltmeter method.

(7) THERMAL FLUCTUATIONS IN NON-METALLIC RESISTORS

The first series of measurements were made with an iron-cored coil having a very small air-gap. The copper losses in this coil were negligible compared with the iron losses. The coil was shunted by a small condenser in series with a resistance of 895 ohms. The combination yielded a fairly symmetrical resonance curve which

Measurements of effective series resistance were made by the two methods described in the last section, fluctuation measurements again being shown by the plotted points. The results are shown in Fig. 8. Agreement is again good, the mean ratio of the results obtained by the two methods being 1·008.

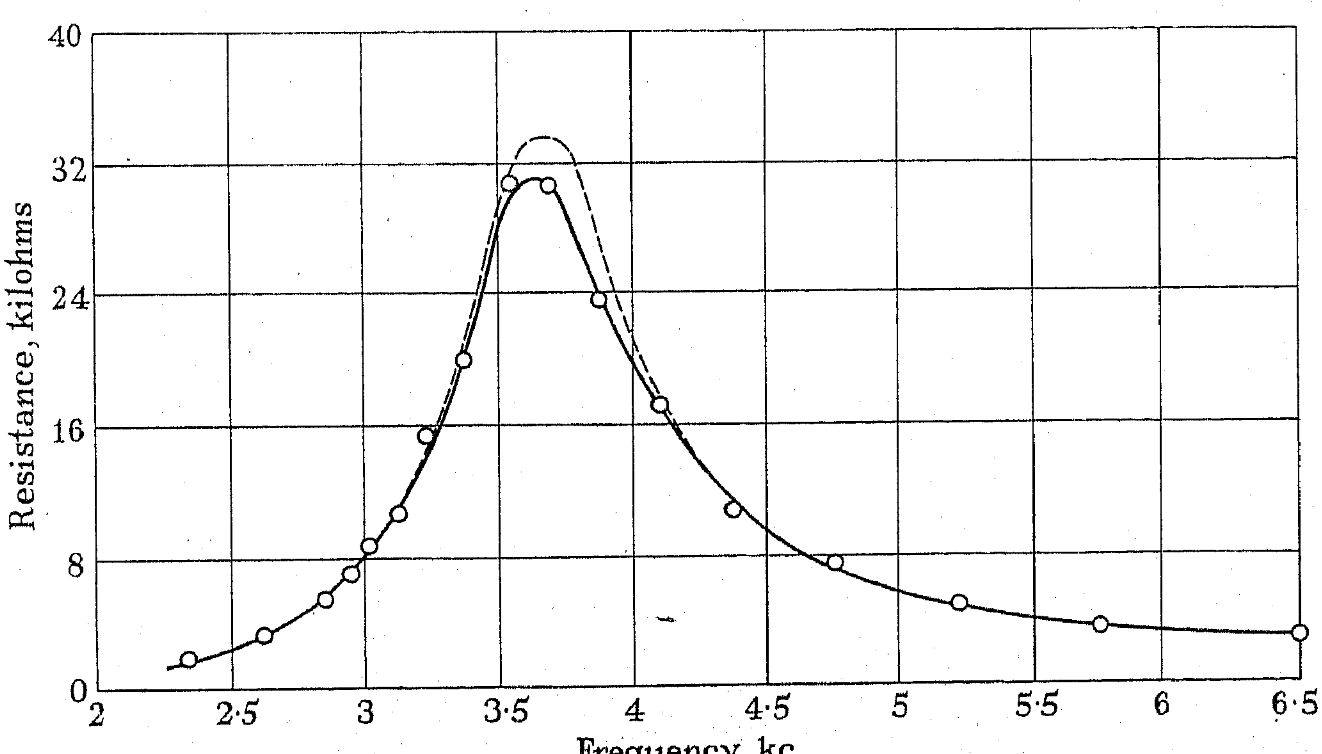

Fig. 8.—Equivalent resistance of a circuit containing iron losses as a function of frequency. Plotted points have been deduced from fluctuation measurements; dotted lines show values obtained by the three-voltmeter method.

Experiments were also made with a small condenser immersed in a polar dielectric. The substance used,

namely Permitol, has been thoroughly examined by Jackson,* who gives the power factor as about 10 % at 6 000 cycles per sec. and 16° C. Several measurements were made at frequencies between 6 000 and 8 000 cycles per sec., but in this case the condenser was used alone as its value was so small as to render it unsuitable for inclusion in a resonant circuit. It was found that resistance values deduced from fluctuation measurements were about 10 % in excess of those obtained by the three-voltmeter method. This is believed to be due to errors in the latter measurement; for the comparatively high ratio of reactance to resistance reduces the accuracy of the method.

Measurements were also made, for another purpose, with a liquid resistance containing a concentration of virus. The method of comparison was similar to that used in the last tests, but the reactance was now negligible. The results obtained from the two methods of resistance measurement differed by less than 1%.

The degree of agreement obtained in all the experiments is felt to be sufficient to verify equation (1*a*), and to show that the relevant value of resistance in this equation is the equivalent power-loss resistance. The general expression, equation (2), relating to networks in which the temperature is not uniform, has not been tested. The experimental difficulties of such a test are considerable and the equation is not of such great practical importance as equation (1*a*). However, the method of representation adopted in the proof of equation (1*a*) given in this paper has been justified, and there appears little reason to doubt the validity of the general equation. Llewellyn† has deduced a formula for the thermal agitation voltage developed by two resistors at different temperatures connected in parallel. His expression can readily be deduced from equation (2) and has been tested experimentally by Moullin and Ellis.‡ They found approximate agreement only, and an exhaustive check is to be undertaken shortly.

NOISE/SIGNAL RATIO

It follows from equation (2) and the derivation given in Appendix 1 that if a signal of sinusoidal wave-form and mean square value e^2 be introduced in the nth branch of a general network, then

$$\frac{|v|^2}{v_s^2} = \left(\frac{Z_{AA'}}{Z'_{AA'}}\right)^2 4kdf \frac{\Sigma r_x \cdot \tau_x / Z_{Ax}^2}{e^2/Z'^2_{An}}$$

where v_s^2 is the mean-square signal output at the points A, A′ and the dashes indicate values of impedance relevant to the frequency of the signal.

If the overall frequency response of the apparatus considered is limited at a later stage to a small finite frequency band δf, the values of the impedances will be sensibly constant within that range; whence, with uniform temperature distribution, we have

(omitting n)

$$\frac{|v|^2}{v_s^2} = 4k\tau\delta f\left(\frac{r_n + Z_{An}^2 \Sigma r_x / Z_{Ax}^2}{e^2}\right)$$

The first term within the brackets is proportional to the (Noise/Signal)^2 ratio in the arm in which the signal is introduced. It follows that the signal/noise ratio cannot be raised above the level obtaining in that arm. This result is perhaps obvious on physical grounds, but the author has previously experienced some difficulty in reconciling it with Nyquist's equation, which bears no obvious relation to conditions in the input arm.

This limiting value of signal/noise ratio is approached when the second term within the brackets is negligible compared with r_n. It follows from equation (3) that such is the case when the resistive component of the impedance from A to A′ is sensibly independent of the resistance values in arms other than the nth: that is, when the terminals A, A′ are heavily loaded by the nth arm. This condition can often be attained in practice, and a few special cases are considered in the following sections.

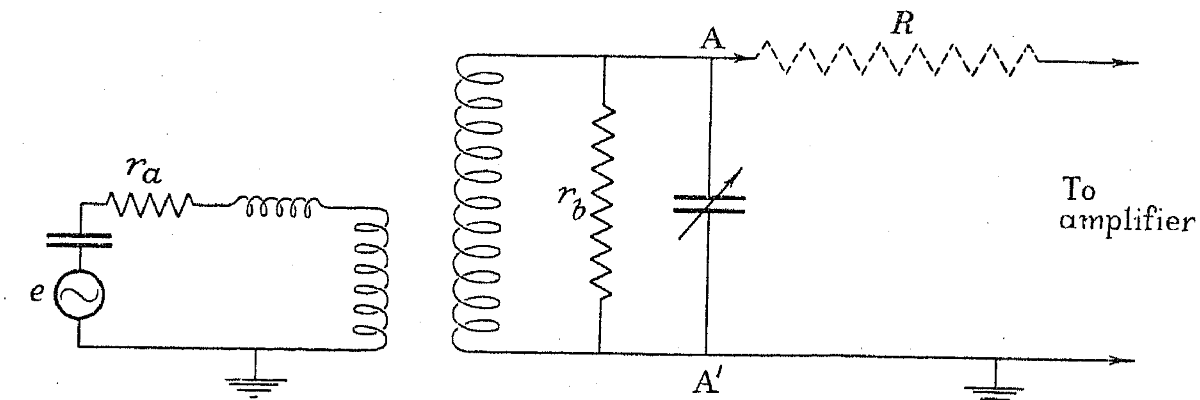

Fig. 9

(9) THE INPUT CIRCUIT OF RADIO RECEIVERS

The aerial is usually coupled to the first amplifying valve through a resonant circuit. Many different circuits are used, but it is sufficient to consider that shown in Fig. 9. The resonant circuit losses are represented by the shunt resistance r_b.

If the associated amplifier responds only to a narrow band of frequencies δf, situated about the resonant frequency of the circuit, it follows from equation (2) that the relevant portion of the thermal agitation fluctuation appearing between A and A′ is

$$|v|^2 = Z_{AA'}^2 4k\tau\delta f\left(\frac{r_a}{Z_{Aa}^2} + \frac{1}{r_b}\right)$$

The total fluctuation output of the receiver is closely equal to the sum of the thermal fluctuations in the first

* See Bibliography, (8). † *Ibid.*, (9). ‡ *Ibid.*, (3).

circuit and the shot fluctuations in the first valve. Pearson* has shown that shot fluctuations can be conveniently represented by an equivalent resistance producing thermal fluctuations in the grid circuit. The total fluctuation output of an amplifier, apart from that due to thermal agitation in the input circuit, can be similarly represented. This equivalent resistance R must be regarded as connected between the circuit and the grid of the first valve, as shown by the dotted lines of Fig. 9. The total fluctuation output referred to the grid of the first valve is then

$$|v|^2 = 4k\tau\delta f Z_{AA'}^2\left(\frac{r_a}{Z_{Aa}^2} + \frac{1}{r_b} + \frac{R}{Z_{AA'}^2}\right)$$

And, with the same notation as before,

$$\frac{|v|^2}{v_s^2} = \frac{4k\tau\delta f \,.\, r_a}{e^2}\left(1 + \frac{r^2 + r_b R}{r r_b - r^2}\right)$$

The term outside the bracket is the (Noise/Signal)^2 ratio in the branch in which the signal is introduced. The expression within the brackets is a minimum when

$$r = R\left[\sqrt{\left(\frac{r_b}{R} + 1\right)} - 1\right]$$

The best signal/noise ratio is therefore obtained when the coupling between aerial and circuit is adjusted so that r has the value given above. Typical values of

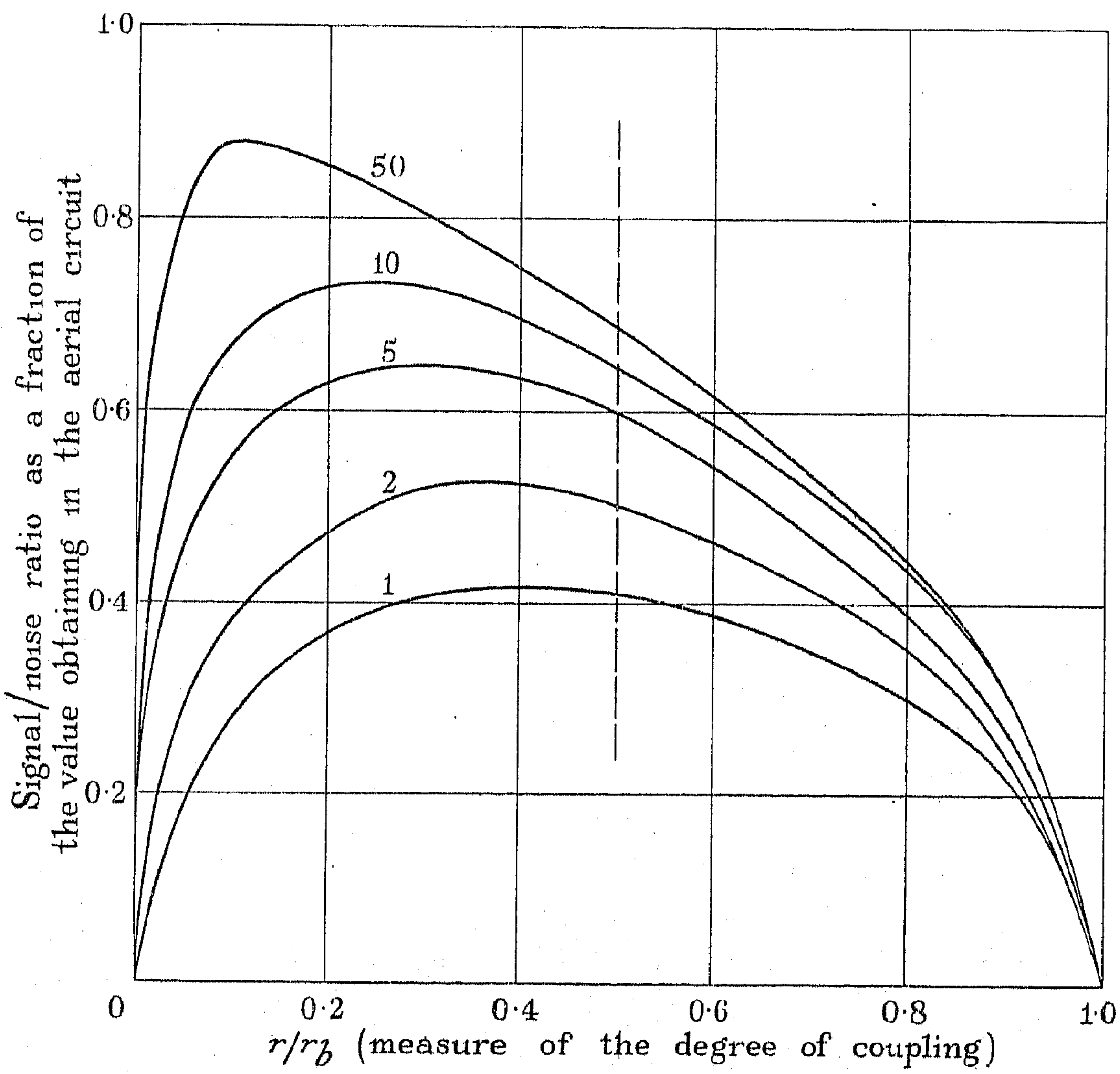

Fig. 10.—Dependence of signal/noise ratio on the degree of coupling between aerial and resonant circuit and on the fluctuations introduced subsequent to the first circuit. The dotted line shows the condition of optimum output. The figures on the curves give the relevant value of r_b/R.

But the reactive component of the impedance from A to A′ is zero, since the circuit is tuned; therefore

$$Z_{AA'} = r$$

Whence, from equation (3),

$$Z_{Aa}^2 = \frac{r_a}{\frac{1}{r} - \frac{1}{r_b}}$$

* See Bibliography, (10).

r_b and R are 50 kilohms and 5 kilohms respectively. With such values the best signal/noise ratio is obtained when the aerial loads the circuit to such an extent that r is about 11·5 kilohms. This value is probably less than that usually adopted, but the adjustment is not usually critical. Thus, with the figures given, the signal/noise ratio varies only about 5 % for values of r between 7·5 kilohms and 20 kilohms, and is within 30 % of the value existing in the aerial circuit. The dependence of the signal/noise ratio on the degree of coupling between aerial and resonant circuit under various circumstances

is shown in Fig. 10. The abscissae of this Figure are values of r/r_b and measure the extent to which the aerial loads the resonant circuit. The ordinates give the signal/noise ratio obtained as a fraction of the limiting value obtaining in the aerial circuit itself. Curves are given for several ratios of circuit-loss resistance to equivalent fluctuation input resistance (r_b/R). Maximum output is always given when $r/r_b = 0 \cdot 5$. This condition is shown by the dotted line in the Figure.

It may be noted that when r_b/R is low, i.e. with circuits of low dynamic resistance and a first valve giving appreciable shot effect, maximum output corresponds closely to optimum signal/noise ratio. On the other hand, a good circuit combined with a quiet amplifier gives the best signal/noise ratio with a coupling closer than that corresponding to maximum output; thus when r_b/R is 50 an improvement of about + 25 % in signal/noise ratio can be obtained by adopting the optimum degree of coupling rather than that corresponding to maximum output.

This circuit has been considered by Llewellyn,* who suggested that maximum-output conditions should always be used. His analysis, however, made no allowance for the fluctuations generated in the anode circuit of the first or subsequent valves.

The practical method of testing a receiver for noise is to note the decrease in noise output as the input circuit is distuned. A large decrease indicates that the bulk of the fluctuation output is due to thermal agitation in the first circuit, and is a measure of r_b/R. Thus if θ_1 and θ_2 are the output deflections due to fluctuation voltages when the input circuit is tuned and distuned (or, preferably, short-circuited) respectively, then

$$\frac{r_b}{R} = \frac{\theta_1 - \theta_2}{\theta_2}$$

The aerial is supposed disconnected in the above tests.

The curves of Fig. 10 then yield the value of r/r_b relevant to optimum signal/noise ratio. If the aerial is connected and the circuit tuned the fluctuation output gives a deflection θ_3 such that

$$\frac{\theta_3 - \theta_2}{\theta_1 - \theta_2} = \frac{r}{r_b}$$

In this way the degree of coupling can readily be set by trial to the value corresponding with optimum signal/noise ratio. Be it noted that it may be necessary to use a dummy aerial in these tests to avoid interference from external sources, such as atmospherics. The optimum is not critical, and therefore the dummy need not be an exact equivalent of the aerial to be used.

(10) BAND-PASS FILTER AS AN INPUT CIRCUIT

If the band-pass filter shown in Fig. 6 is used as an input circuit for a radio receiver the aerial is coupled to the left-hand branch and the receiver to the right-hand branch. If satisfactory filter operation is to be obtained neither branch must be appreciably damped by such connection. The aerial must therefore be lightly coupled to the filter. This requirement is completely inconsistent with the condition for optimum signal/noise ratio, which demands that the aerial be responsible for the bulk of the input-circuit damping. Thus, if a good signal/noise ratio is required the filter characteristic must be sacrificed and the simpler and more efficient single circuit will give equal results as regards frequency response.

The exact analysis of the circuit is complex, but it is clear from the above discussion that band-pass filters should not be used if fluctuation noise is an important consideration.

(11) FLUCTUATION VOLTAGE IN CABLES

If the characteristic impedance of a cable is $(r_a + jx_a)$, where x_a is usually small, the fluctuation voltage in the small finite range δf appearing across the end of the cable is

$$|v|^2 = 4r_a k\tau\delta f$$

If the length of the cable be l and the attenuation per unit length $\epsilon^{-\alpha}$, then with uniform temperature the signal/noise ratio at the receiving end due to a signal E at the sending end is

$$\frac{E\epsilon^{-\alpha l}}{\sqrt{(4r_a k\tau \,.\, \delta f)}}$$

Reference to equations (2) and (3) shows that if the temperature is not uniform, but the attenuation is appreciable, the same expression holds provided τ is the temperature in the vicinity of the receiving end. The physical explanation is that it is unnecessary to consider temperature conditions elsewhere in the cable since the fluctuations there produced are severely attenuated before arriving at the receiver.

If the cable is of low characteristic impedance it is usual to step up the impedance by means of a resonant circuit or transformer, in order that valve noise shall not be predominant. In such cases the equivalent circuit is very closely approximate to that considered in Section (9), and the conditions for optimum signal/noise ratio deduced in that section are applicable. An identical experimental procedure can be adopted to determine the optimum degree of coupling.

(12) CONCLUSIONS

Thermal agitation fluctuations in any linear network can be regarded as due to equivalent fluctuation generators of mean square output voltage $4r_a k\tau_a df$, $4r_b k\tau_b df$, etc., acting in series with the resistances r_a, r_b, etc. The fluctuation output between any two points in the network is then given by equation (2). If the network is at a uniform temperature then Nyquist's equation (1a) is valid as a special case of equation (2). The resistance relevant to this formula is the equivalent power-loss resistance.

The best signal/noise ratio is obtained when the loading between the observation points is due mainly to the arm in which the signal is injected.

When a resonant circuit or transformer is used to couple an aerial or cable to the first stage of an amplifier, there exist optimum conditions as regards signal/noise ratio which are dependent on the losses in the circuit or

* See Bibliography, (11).

transformer and the fluctuations subsequently introduced in the amplifier. The optimum condition has been discussed in Section (9).

The signal/noise ratio in a long cable is best when the ratio of attenuation per unit length to the square root of the characteristic impedance is greatest. The temperature of the cable in the vicinity of the receiving end is the only important temperature.

Band-pass filters or other filters should not be used to couple aerials or cables to amplifiers, as the signal/noise ratio is thereby reduced.

ACKNOWLEDGMENT

The research described in this paper was begun in the Engineering Laboratories of Oxford University and completed in the Electrotechnics Department of Manchester University. The author is indebted to Mr. E. B. Moullin for his interest in the work, and to Prof. R. Beattie for later facilities.

APPENDIX 1

Fig. 11 represents any network of linear impedances of which r_x is a typical resistance element. A generator G

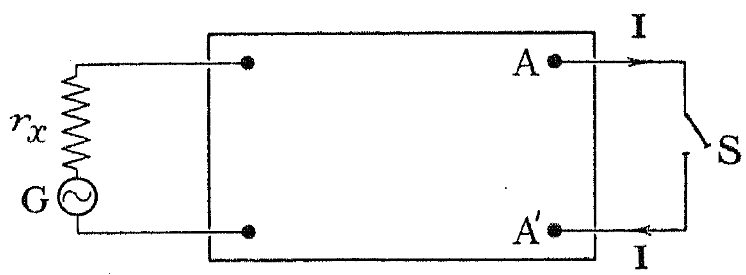

Fig. 11.

is supposed connected in series with r_x. A and A′ are any two points in the network and are furnished with a switch S by means of which they can be short-circuited.

First suppose that the generator delivers a sinusoidal output $\mathbf{E}$ of the form $e = e_{max.}\ \sin \omega t$, and that the switch is closed. Then the current $\mathbf{I}$ flowing from A to A′ as shown is

$$\mathbf{I} = \frac{\mathbf{E}}{\mathbf{Ax}}$$

where $\mathbf{Z_{Ax}}$ is the vector transfer impedance from the generator to the short-circuit across AA′ relevant to the frequency $\omega/(2\pi)$. The mean-square value of i is

$$I^2 = \frac{e^2_{max.}}{2} \frac{1}{Z^2_{Ax}}$$

where Z_{Ax} is the modulus of the transfer impedance.

It follows that if the sinusoidal generator be replaced by an equivalent thermal agitation source yielding an output given by

$$|\, v\,|^2 = 4r_x k\tau_x df$$

where df is supposed situated about the frequency $\omega/(2\pi)$, then the mean-square value of the fluctuation current, flowing through the switch due to thermal agitation in r_x, is

$$|\, i_x\,|^2 = 4kdf \cdot \frac{r_x \tau_x}{Z^2_{Ax}}$$

Similar fluctuation currents due to every other resistance element in the network flow in the short-circuit AA′. The mean-square value of the sum of any number of mutually independent fluctuation voltages or currents is the sum of their mean-square values: hence the total fluctuation current through the switch is

$$|\, i\,|^2 = 4kdf \sum \frac{r_x \tau_x}{Z^2_{Ax}}$$

Suppose now that the fluctuation sources are removed and the switch opened, and that owing to some impressed sinusoidal e.m.f. in the network there exists across the switch a p.d. $\mathbf{E}$. If now the switch be closed, according to Thévenin's theorem* there will flow through the switch a current

$$\mathbf{I} = \frac{\mathbf{E}}{\mathbf{Z_{AA'}}}$$

where $\mathbf{Z_{AA'}}$ is the network impedance from A to A′.

Conversely, if the fluctuation current of mean-square value $|\, i\,|^2$ obtained under the previous conditions is interrupted by opening the switch, there will appear across the switch a mean-square fluctuation voltage given by

$$|\, v\,|^2 = Z^2_{AA'} 4kdf \sum \frac{r_x \tau_x}{Z^2_{Ax}}$$

which is the fluctuation voltage appearing between A and A′. This relation is equivalent to equation (2).

APPENDIX 2

Considering the same network as in Appendix 1, let an e.m.f. $\mathbf{E}$ of the form $e = e_{max.}\ \sin \omega t$ be applied across the points A and A′, it being supposed that fluctuation voltages are absent. Then the current in the resistance r_x is

$$\mathbf{I_x} = \frac{\mathbf{E}}{\mathbf{Z_{Ax}}}$$

where $\mathbf{Z_{Ax}}$ is now the transfer impedance from the generator to the arm r_x, but is the same as the $\mathbf{Z_{Ax}}$ already defined, since in linear networks the transfer impedance is the same in both directions.

The power loss in r_x is

$$p_x = r_x |\, i_x\,|^2 = \frac{1}{2} r_x \frac{e^2_{max.}}{Z^2_{Ax}}$$

The total power loss in the network is the sum of all such terms as p_x, and is given by

$$p = \frac{1}{2} e^2_{max.} \sum \frac{r_x}{Z^2_{Ax}}$$

But if $\mathbf{Z_{AA'}}$ has the form $(r + jx)$ the current entering the network is $\mathbf{I} = \mathbf{E}/\mathbf{Z_{AA'}}$, and the power loss can be expressed as

$$p = r\,|\,\mathbf{I}\,|^2 = \frac{1}{2} e^2_{max.} \frac{r}{Z^2_{AA'}}$$

* See, for example, T. E. Shea: "Transmission Networks and Wave Filters," p. 55 (New York, 1929).

Whence, by comparison of the two expressions for p,

$$r = Z^2_{AA'} \sum \frac{r_x}{Z^2_{Ax}}$$

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THE USE OF PROTECTIVE MULTIPLE EARTHING AND EARTH-LEAKAGE CIRCUIT BREAKERS IN RURAL AREAS

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[REPORT (REF. F/T112) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

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SUMMARY

This paper describes investigations made to ascertain to what extent consumers in rural areas are protected from risk of shock with methods of earthing at present in use, and what changes in practice might be desirable, with special reference to protective multiple earthing.

The investigation shows that present safeguards are inadequate. Recommendations are made which it is believed will lead to material improvement, but further experience and experiment will be necessary before the matter can be put on an entirely satisfactory footing.

It has been realized for some time that in rural areas fed by overhead lines where no water mains exist the protection afforded by "ordinary earthing" is not entirely satisfactory. With this in mind an investigation was undertaken by the E.R.A. with a view to finding means for improving the situation.

Alternative methods of protection are provided by earth-leakage circuit breakers,* or the use of the neutral to carry the fault current. This latter method, known throughout this paper as "protective multiple earthing," is subject to the disadvantage that the frameworks of apparatus connected to the neutral rise to the same voltage above earth as the neutral conductor.

It was found from field tests, however, that the voltage-rise of the neutral did not exceed a value dangerous to human beings under normal operation, and that even animals would be protected if the statutory voltage-drop were not exceeded. No interference with the satisfactory working of the telephone system was observed during any of the tests.

Other possible sources of trouble due to the use of the protective multiple earthing system have been considered in some detail.

An investigation has also been made to find the tripping voltage of earth-leakage circuit breakers which have been in use for a period of about 2 years. The tests were made by Mr. E. Fawssett in the electricity supply area of the Dumfriesshire County Council.

The paper concludes with the major deductions reached from the practical tests, some conclusions respecting protective multiple earthing in general, and, finally, recommendations respecting existing and new installations and certain proposed conditions which should be complied with before protective multiple earthing is permitted.

The Director of the E.R.A. will welcome comments from any who may have occasion to make use of this paper.

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(5) Practical Tests on Earth-Leakage Circuit Breakers.

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(7) Conclusions and Recommendations.
- (*a*) Conclusions on the practical tests.
- (*b*) Conclusions on protective multiple earthing in general.
- (*c*) Recommendations.
- (*d*) Proposed conditions which should be complied with where protective multiple earthing is used.

(8) Acknowledgments.

(1) INTRODUCTION

It is a matter of primary importance that, when providing a supply of current to a consumer, adequate measures should be taken to ensure that the use of the supply does not involve risks to the consumer during normal operation, and that in the event of the failure of these measures the supply will be cut off in a short period of time. As is well known, the insulating material which is used for protection in normal service is liable to deteriorate, and for this and various other reasons live metal-work may make contact with non-current-carrying metal parts, and a potential danger then exists, since the consumer may touch the metal part at the same time as some other earthed object and receive an electric shock.

To provide for this contingency it has been the general custom in the past, in this country, to connect non-current-carrying metal parts to earth* so that, in the event of a breakdown of insulation occurring, current will return via the earth to the earthed neutral point

* Often referred to as "earth-leakage switches" or "earth-leakage trips."

* Throughout the paper this arrangement is known as "ordinary earthing."

of the system and will be of sufficient magnitude to blow the fuses on the faulty circuit. This method of protection is satisfactory, provided that the total impedance in the circuit, which is made up of the supply lead, transformer winding, fault connection, earth-continuity conductor, and earth electrodes, is sufficiently low to pass an adequate current. In urban areas it is usual to earth to water-mains or the lead sheath of the service cable, and in these cases there is no difficulty in obtaining a sufficiently low resistance, provided that the house wiring is carried out satisfactorily and the resistance of the earth-continuity conductor does not exceed that prescribed by the " I.E.E. Regulations for the Electrical Equipment of Buildings."

In rural areas the problem is different. The supply is usually overhead, and frequently no water-mains exist. It is then necessary to earth by means of a pipe, rod, or plate electrode which may have any resistance from one ohm to several thousand ohms. At the substation it is possible in many parts of the country to obtain a resistance of about one ohm, but to take similar measures at consumers' premises would frequently make the cost of installation prohibitive. Although this situation is fairly generally known, new installations continue to be earthed in the old way where there is very little likelihood of a fuse ever blowing as the result of an earth fault.

To continue to go to the trouble of earthing where the resistance is so high as to prevent the blowing of the smallest fuse is a waste of money, and to carry an earth-continuity conductor all over the premises only ensures that a fault on one piece of apparatus will make all the other apparatus alive.

This problem is not peculiar to Great Britain, and has been solved elsewhere by the use of the neutral as a return conductor for the fault current, or by earth-leakage circuit breakers in which the supply is interrupted by means of a trip coil which operates when the protected metal-work reaches some potential above earth. The use of these leakage circuit breakers is called for by the I.E.E. Regulations in certain cases, and they are being used in increasing numbers to-day.

The position is different with respect to the use of the neutral as a means of protection. Apart from concentric wiring systems and a low-voltage cable system at Aspley Guise, Bedfordshire, the neutral is not used at all for protective purposes in this country, though it is used to a considerable extent in America, on the Continent, in New Zealand, and in the Irish Free State. Articles frequently appear in English technical journals criticizing the system, but it is considered that these criticisms may not necessarily be valid in this country, and the possibility of the system being used should not be rejected without practical tests.

As the result of careful inquiries with reference to the position abroad the Association has reached the following conclusions:—

(*a*) That protective multiple earthing is used in various countries with reasonable satisfaction.

(*b*) That the major objection to the system arises from the danger of a broken neutral conductor, and that the frequency of this occurrence abroad and its rarity in this country is due to a substantial difference in the methods of construction of l.v. distribution systems.

(*c*) That earth-leakage circuit breakers are giving reasonable satisfaction but that their advantages over protective multiple earthing have not resulted in the general displacement of the latter system. For example, in Germany, where the earth-leakage circuit breaker originated, protective multiple earthing is used by many companies in rural and urban installations. Other companies, notably the Rheinisch Westfalisches Elektrizitätswerk, have completely changed over to earth-leakage circuit breakers.

(2) TERMINOLOGY

Before proceeding further it is desirable that something should be said about terminology. It is unfortunate that the term " multiple earthing " has several meanings which are commonly used. These are set out below.

Multiple earthing may mean—

(*a*) The connection to earth of the star points of a number of transformers on one high-voltage network—the object is to facilitate the operation of protective gear, and the method is used on the grid system.

(*b*) The connection to earth of the neutral points of a number of transformers on one low-voltage system—this is frequently done when a number of transformers feed a ring main. Usually the ring is closed some time after the transformers have been operating independently, and the redundant earths are not removed.

(*c*) The connection to earth of an l.v. neutral conductor at a number of points in order to obtain a low earth resistance for the neutral point of the transformer.

(*d*) The connection to earth of the neutral conductor at some or all consumers' premises and the connection of metal frameworks to the neutral. There are several variations of this, as follows:—

(i) The earth-continuity conductor may be run through the house and connected to the neutral and to earth at the meter board.

(ii) All metal-work may be connected to the (insulated) neutral at the appliances themselves.

(iii) The neutral may be run as a bare wire and connected to all metal-work.

(*e*) The connection in parallel of a number of earth electrodes.

The last meaning is not generally used in this country and may be disregarded, but the other meanings are all in fairly general use, and it is necessary to distinguish between them. (*c*) is accurately described as multiple earthing of the neutral, and (*d*) is really a combination of (*c*) and the connection of frameworks to the neutral. This is the meaning with which we are at present most concerned. To call it " multiple earthing " or " M.E.N."

is inadequate and confusing, but at the same time an accurate description such as "multiple earthing of the neutral with connection to the neutral of frameworks" is too long. It is therefore suggested that the phrase "protective multiple earthing" be used as a short title, and that wherever possible the method be described as "use of the neutral for protective purposes."

Throughout this paper this terminology will be used, and it should be understood to refer only to variation (i) of meaning (*d*). Variations (ii) and (iii) are subject to serious disadvantages, and (iii) is not considered in detail.

was always 10 ohms or less, and the figure shows a clear discontinuity in the curve, at 10 to 15 ohms, between the resistance of pumps, water systems, etc., and that of earth rods or plates. It is noteworthy that the results for the four places are fairly uniformly distributed over the range of resistance covered, irrespective of the type of soil and the supply undertaking. The resistances were measured with a four-range "Megger" earth tester.

No special attempt had been made to obtain particularly low resistances at any of these villages, and the results may be regarded as typical of many villages throughout the country.

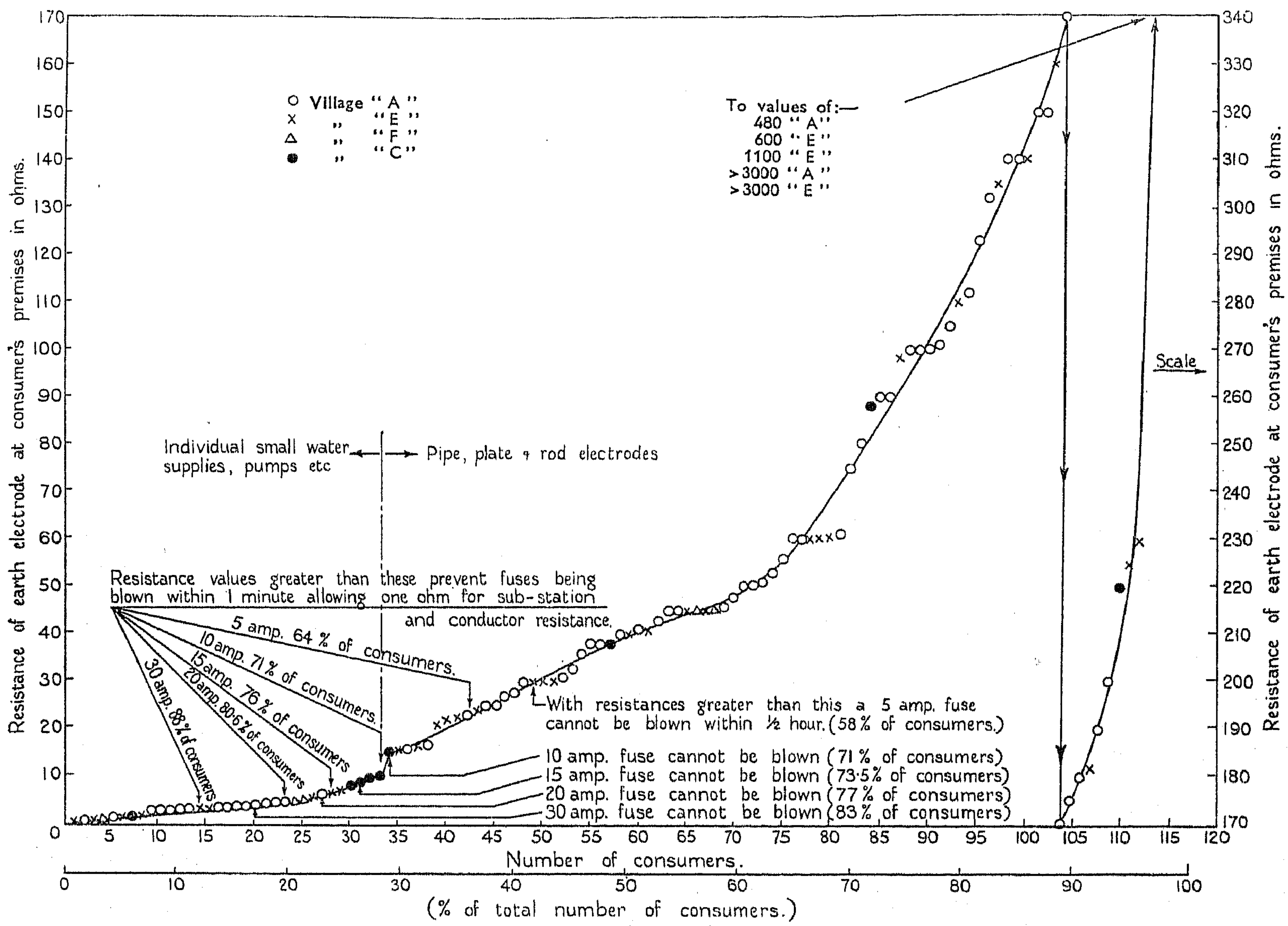


Fig. 1.—Resistance of earth electrodes at consumers' premises.

(3) PROTECTION EFFECTED BY PRESENT METHOD OF EARTHING

The tests which are described later in this paper provided an opportunity for measuring the resistance of earth electrodes at consumers' premises at four villages in various parts of the country.

The results obtained are plotted in increasing values in Fig. 1, and it will be seen that they range from 0·35 ohm to over 3 000 ohms. Twenty-five per cent of the values are below 10 ohms, 35 % between 10 and 50 ohms, and the remaining 40 % over 50 ohms. In none of the villages does a general system of water-mains exist, though in many cases it was found that consumers had a pump which drew water from a well in the garden, and these were generally used for earthing. The value

According to the British Standard Specification for fusible cutouts (B.S.S. No. 88) a fuse must carry 60 % overload for half an hour, and according to the I.E.E. Regulations it must blow within 1 minute at 100 % overload. These conditions enable the permissible value of resistance to be determined in the earth circuit to ensure that various sizes of fuse shall blow in a minute or in half an hour. On a 240-volt supply we find that if the resistance exceeds $150/I$, where I is the normal carrying current of the fuse, the fuse will not blow within half an hour. The values for fuses of 5, 10, 15, 20, and 30, amperes are 30, 15, 10, 7·5, and 5 ohms, respectively. If we allow 1 ohm for the resistance of the earth at the substation it is possible to find from Fig. 1 the proportion of consumers' installations in the four villages considered where

the various sizes of fuse cannot be blown in half an hour. The results are as follows:—

At 58 % of consumers' installations a 5-ampere fuse cannot be blown in half an hour.

At 71 % of consumers' installations a 10-ampere fuse cannot be blown in half an hour.

At 73·5 % of consumers' installations a 15-ampere fuse cannot be blown in half an hour.

At 77 % of consumers' installations a 20-ampere fuse cannot be blown in half an hour.

At 83 % of consumers' installations a 30-ampere fuse cannot be blown in half an hour.

If the fuse is to blow within one minute—a much longer period than an earth fault should be allowed to persist—then the resistance must not exceed $120/I$. Allowing as before a resistance of 1 ohm at the substation, the values of resistance at the consumers' earth electrodes are 23, 11, 7, 5, and 3, ohms for fuses rated at 5, 10, 15, 20, and 30, amperes. These resistances are marked with

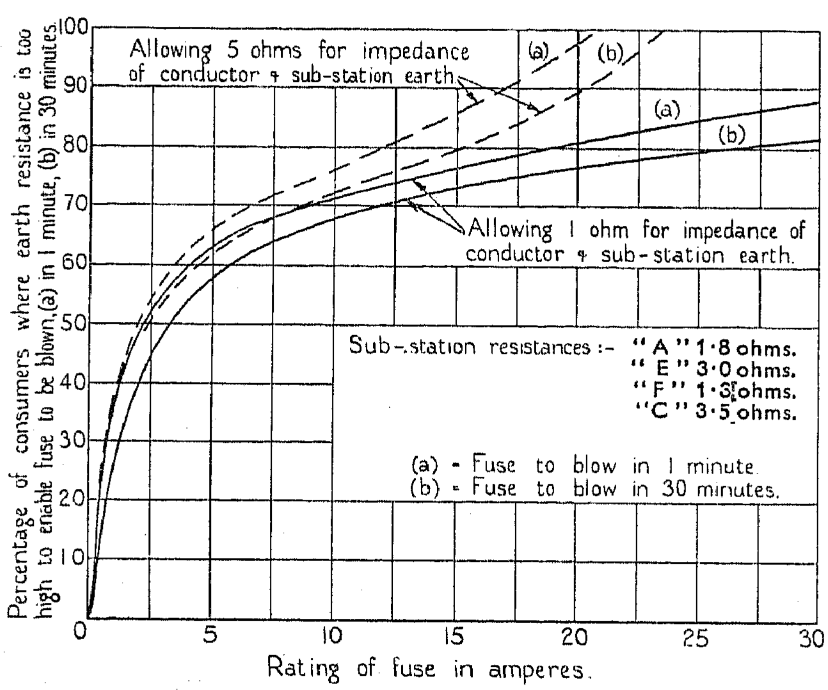


Fig. 2.—Percentage of consumers at each of the villages where various sizes of fuse cannot be blown.

arrows on the left-hand side of the diagram in Fig. 1, and the proportions of consumers with greater resistances where the various fuses cannot be blown are as follows:—

At 64 % of consumers' installations a 5-ampere fuse cannot be blown in 1 minute.

At 71 % of consumers' installations a 10-ampere fuse cannot be blown in 1 minute.

At 76 % of consumers' installations a 15-ampere fuse cannot be blown in 1 minute.

At 80·6 % of consumer's installations a 20-ampere fuse cannot be blown in 1 minute.

At 88 % of consumers' installations a 30-ampere fuse cannot be blown in 1 minute.

In addition to this it should be noted that a resistance of only 1 ohm in the conductors and at the substation is very low for a rural area,* and also that all the resistances were measured between October and March in a very wet winter. Another interesting point is that of the installations using a rod or plate electrode *none* would blow a 10-ampere fuse in 1 minute and only 10 % would blow a 5-ampere fuse.

* It is lower than occurred at any of the four villages considered.

In Fig. 2 the size of fuses has been plotted against the percentage of consumers' installations where the fuses could not be blown in (*a*) 1 minute and (*b*) half an hour for two values of substation earth-electrode resistance. The values are 1 ohm, which is very low (considering that it includes the impedance of the earth-continuity conductor, and the phase conductor from the transformer to the fault), and 5 ohms, a value which there should be no particular difficulty in obtaining almost anywhere. The resistances at all the four villages fall within this range.

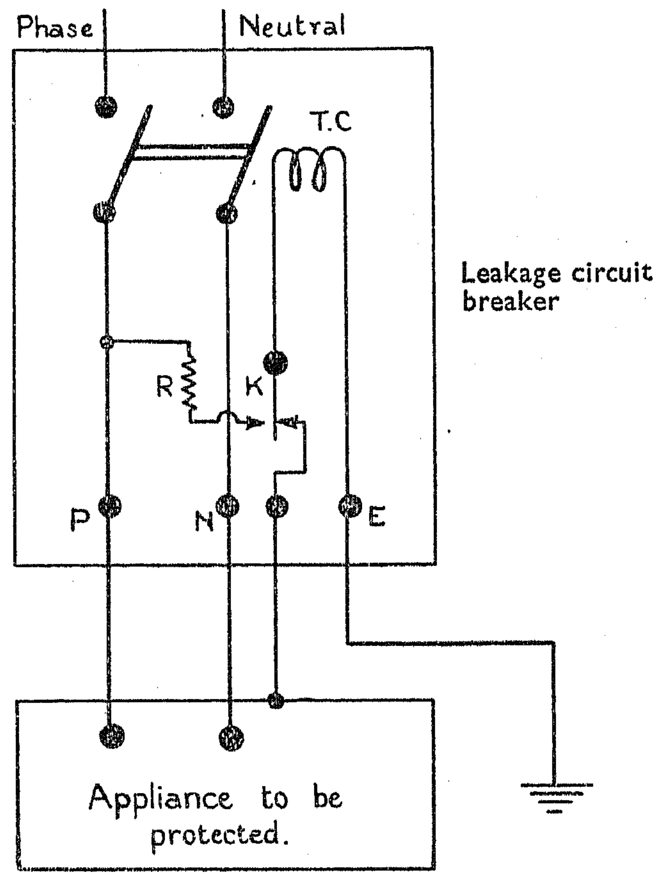


Fig. 3.—Diagram of connections of earth-leakage circuit breaker.

With a 5-ohm resistance it will be seen that 66 % of all consumers' installations could not blow a 5-ampere fuse in 1 minute, 77 % could not blow a 10-ampere fuse, 86 % could not blow a 15-ampere fuse, and 98 % could not blow a 20-ampere fuse. If a fault occurs and the fuses do not blow, then the full supply voltage may exist between the metal-work of the defective apparatus (and all other interconnected metal-work) and earth.

(4) ALTERNATIVE METHODS OF PROTECTION

(a) Earth-Leakage Circuit Breakers.

(*i*) *At Consumers' Premises.*

A diagram of connections of the simplest form of earth-leakage circuit breaker is shown in Fig. 3. In the event of an earth fault on the appliance to be protected current flows to earth via the trip coil (T.C.), and so opens the circuit breaker. The current at which the trip coil operates varies from 20 to 60 mA in the case of five makes of circuit breaker available on the market,

and the a.c. voltage required to operate them varies from 10 to 25 volts.*

To provide a check on the operation of the circuit breaker, and the continuity of the earth connection, a test key (K) is frequently provided by means of which the trip coil may be connected from the phase wire to earth through a limiting resistance R. This key is sometimes arranged to make contact first with one side of the supply and then the other, to allow for mistakes in wiring-up in which the phase and neutral wires are interchanged. It is usual for the key when depressed to break the connection between the trip coil and the appliance, to prevent the framework being connected to the line through the limiting resistance R.

Fig. 4 shows the conditions under which earth-leakage circuit breakers operate on 240-volt supplies. The voltage which is available to trip the coil depends on the position with respect to the neutral end of the appliance element at which the fault occurs, and the impedances in the circuit, viz. the trip-coil impedance, the fault impedance, and the earth-electrode impedance (the impedance of lines and substation earth electrode may be neglected). If these impedances are represented by R_c, R_f, and R_e, respectively, the percentage distance from the neutral end of the element by a, and the current in milliamperes required to operate the trip coil by i, then for a 240-volt supply we may write:—

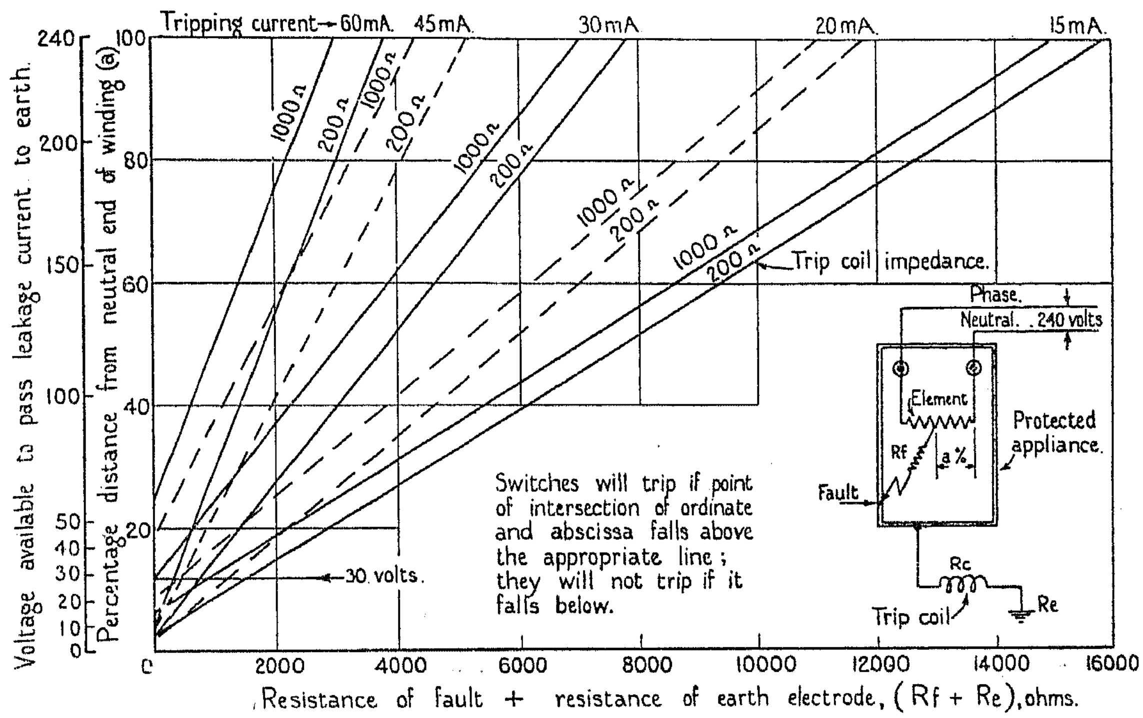


Fig. 4.—Conditions for operation of earth-leakage circuit breakers on 240-volt supplies.

$$i = 2\,400a/(R_f + R_c + R_e)$$

The relationship between $(R_f + R_e)$ and a shown in Fig. 4 is obtained from this equation by substituting values of 15, 20, 30, 45, and 60 mA for i and values of 200 and 1 000 ohms for R_c. From this diagram it is possible to determine for a given type of circuit breaker, of which the trip-coil impedance and operating currents are known, whether it will operate for particular values of a and $(R_f + R_e)$. For example, if the tripping current of a circuit breaker is 30 mA, its impedance 600 ohms, and a fault occurs on the appliance midway between the two ends of the winding, the breaker will trip out if the combined resistance of the fault and the earth electrode is less than 3 400 ohms. On the other hand, if the tripping current is 60 mA, the impedance 200 ohms, and a fault occurs at a point 30 % away from the neutral terminal, the breaker will not operate unless the resistance of the fault and earth electrodes combined is less than 1 000 ohms. If the resistance exceeds this value, 30 % of the supply voltage, i.e. 72 volts, will be impressed on all the metal-work, and a shock could be obtained by making contact therewith.

It has been agreed by the E.R.A. that the maximum potential which should be tolerated permanently on metal frameworks is 30 volts, and it is therefore desirable that all leakage circuit breakers should be so arranged that, at least when the fault resistance is zero, they will operate at this value. On examining the diagram it will be seen that to permit this the earth resistance must not be greater than 1 500 ohms, but as it is unlikely that breakers operating at 15 or 20 mA will have coil impedances as low as 200 ohms, it would be safer to take a value of 1 000 ohms for the earth resistance. In the case of the circuit breakers of which details were given earlier, the limiting values of earth resistance for operation at 30 volts vary from 160 to 630 ohms. There should be no difficulty in obtaining such values, but in view of the fact that 10 % of the resistances measured at the various villages referred to earlier in this paper were greater than 160 ohms, it is clear that a certain amount of care will still need to be exercised in effecting the earth connection.

There is no doubt that these circuit breakers provide a solution to the problem of protecting consumers from shock in rural areas, and they are widely used for this purpose on the Continent. On the other hand, there are certain well-known disadvantages which it is well to point out.

* Figures kindly supplied by Mr. G. F. Shotter.

(i) Either a separate circuit breaker is required for each appliance or group of appliances, which in small installations may represent a fairly heavy cost, or if only one breaker is installed at the consumers' terminals then a fault on any one appliance will cut off the whole supply.

(ii) The test key does not test the continuity of the earth wire between the circuit breaker and the appliance, but this may be done by momentarily connecting the live side of the supply to the appliance framework, when the breaker should operate.

(iii) If a metal case and test key are used with the leakage circuit breaker no protection is afforded against an insulation failure on the breaker itself.

(iv) Cooker elements of the type using a ceramic insulating material may have such a low insulation resistance when first switched on that sufficient current will flow to earth to trip the leakage circuit breaker.

(v) If the resistance of the body is comparable with that of the earth resistance of the leakage circuit breaker, and the current through the trip coil is insufficient to operate it, an unpleasant, and in exceptional cases dangerous, shock may be received from the live metal-work.

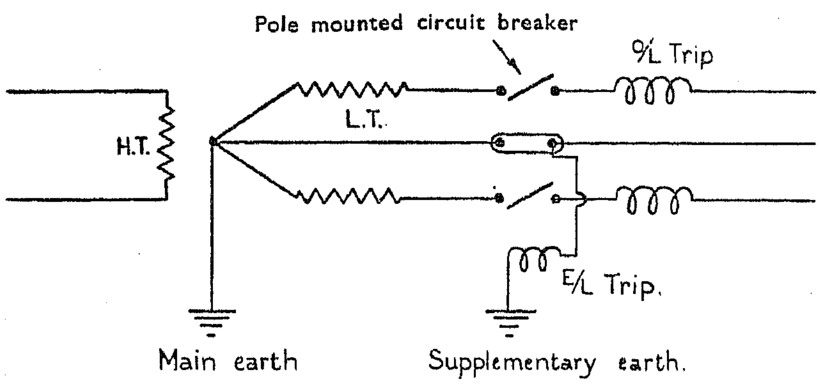


Fig. 5.—Substation earth-leakage circuit breaker.

Earth-leakage circuit breakers also have an outstanding advantage over methods of protection depending on the blowing of a fuse, viz. that their operation depends in any installation on the voltage of the protected metalwork above earth, and this is the factor which gives rise to a shock danger. With other methods, although the resistances may be such that a dead earth fault will be cleared, it does not follow that a fault from a point on the element or winding not near the live end will clear, owing to the reduced voltage available. The fault may also have appreciable resistance, which will prevent sufficient current flowing but at the same time give rise to a dangerous potential above earth on the framework.* With faults of this nature the earth-leakage circuit breaker scores a distinct advantage over other methods.

* Assuming that 25 mA is a dangerous current to pass through the body, a dangerous shock may be obtained from earthed apparatus on a 250-volt supply if the resistance of the fault is less than

$$R\left(\frac{10\,000}{r} - 1\right)$$

where

R = resistance of earth electrode, and
r = resistance of the body.

See page 8 of Ref. F/T82: "Electric Shocks from Earthed Apparatus," by H. G. Taylor.

(ii) *At Substations.*

Earth-leakage circuit breakers may also be used at substations as shown in Fig. 5.* The circuit breakers are pole-mounted in weatherproof cases suitable for outside use. The earth connection is in parallel with the main earth and carries a proportion of the total current determined by the ratio of the impedance of the supplementary earth plus the trip coil to the impedance of the main earth. Further details of the circuit breaker are given in Section (4) (*b*) (iv).

(b) Use of the Neutral for Protective Purposes.

By connecting all metallic frameworks to the neutral conductor one ensures that, in the event of the breakdown of insulation, current returns via a metallic conductor to the substation, and the prospects of blowing the fuse are very much higher than they would be if the resistance of two earth electrodes were included in the circuit. There are two general methods of effecting the connections between frameworks and neutral; they may be made (1) at each appliance, or (2) at the meter board only with an earth-continuity conductor run throughout the installation. The former method is shown in Fig. 6 and the latter in Fig. 7.

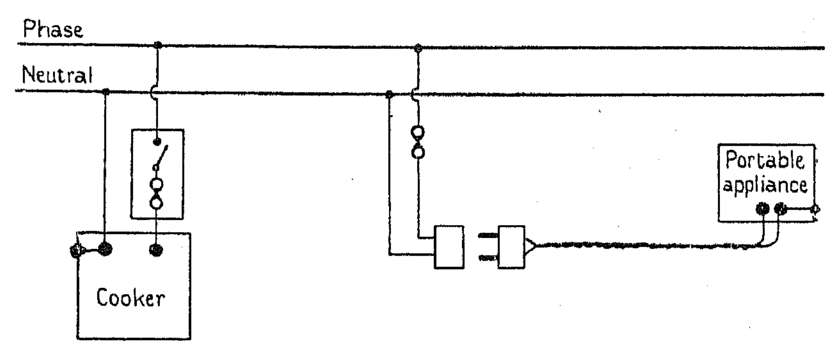


Fig. 6.—Connection made to neutral at each appliance.

(*i*) *Neutral Connection made at each Appliance.*

If the connections are made at each appliance then it is clear that no fuses or switches can be allowed in the neutral, since if the neutral becomes disconnected without the phase wire all appliances on the remote side of the disconnections have their frameworks connected to the live wire and are potentially dangerous. A similar condition can exist if a plug is inserted the wrong way round; if the wiring to the socket is incorrect; if the wiring of the plug or appliance is incorrect; or if the neutral conductor in the flexible cord breaks. The possibilities of a dangerous condition are in fact so numerous that no one would seriously suggest such an arrangement. The majority of the difficulties are overcome if a 3-core flexible cord and 3-pin plugs and sockets are used, with the connection between the earth pin and the neutral conductor made at the socket.

Even with this arrangement there are, however, three objections, viz.:—

(1) The socket may be wired up incorrectly.

(2) Reliance must be placed on the continuity of the neutral wire throughout the installation for protective purposes.

* T. C. Gilbert: "Artificial Earthing for Electrical Installations" (Benn, London, 1932, p. 111).
D. Ross: "A Review of Recent Developments in Rural Electrification," *I.E.E. Journal*, 1936, pp. 810, 815, 825.

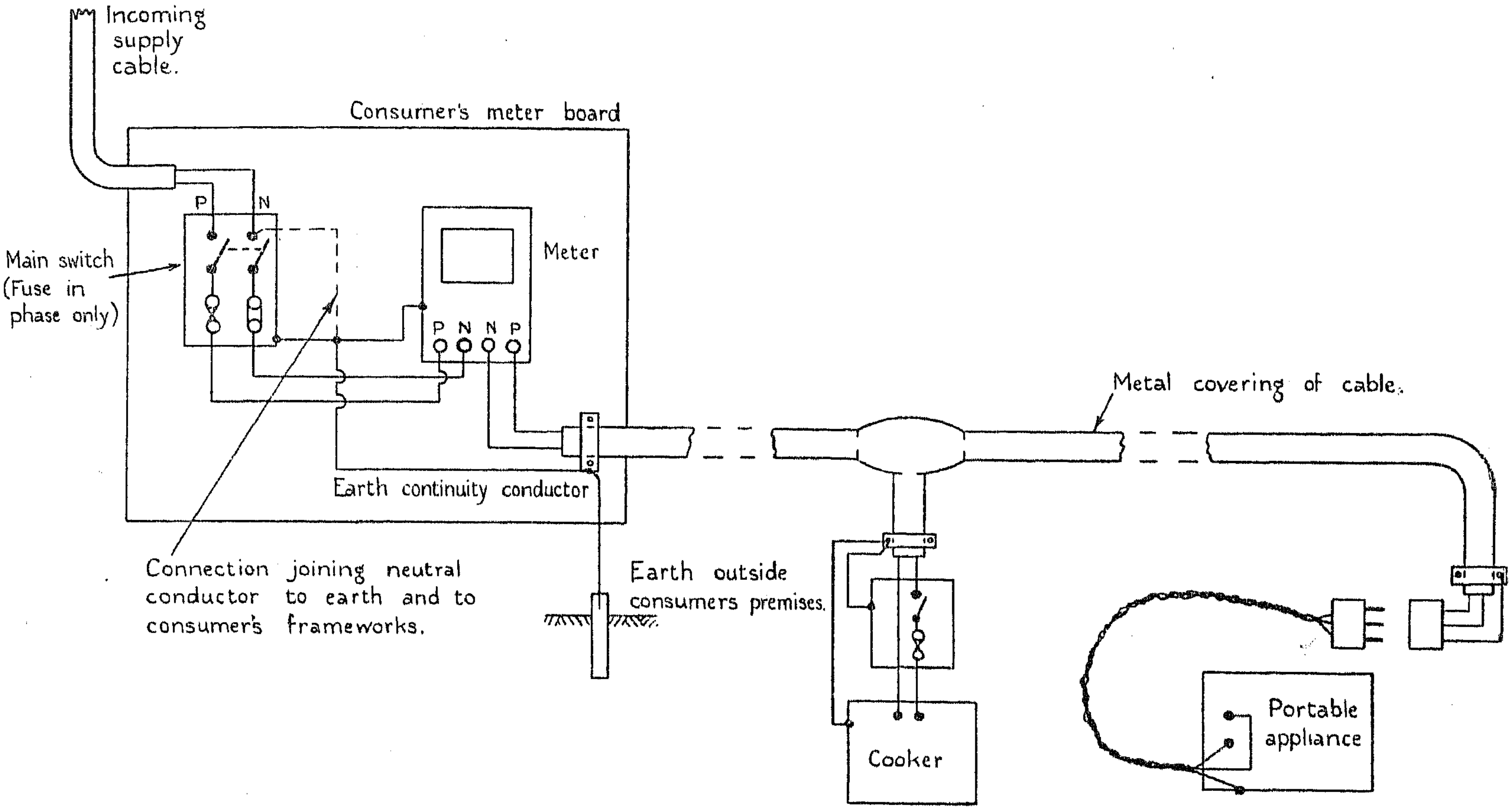


Fig. 7.—Connection made to neutral at meter board only.

(3) With any system of protective multiple earthing, frameworks may rise to the voltage above earth of the neutral—with the arrangement considered one includes the voltage-drop on the neutral conductor within the installation, which may be a considerable proportion of the total voltage-drop.

(*ii*) *Neutral Connection made at the Consumers' Terminals.*

The preferable arrangement is one in which the frameworks are all connected together with an earth-continuity conductor which is connected to the neutral and to earth at the consumers' terminals. This arrangement for an installation having lead-covered wiring is shown in Fig. 7. This is the method of wiring used in many rural installations, and the earth-continuity conductor already exists. To convert the installation from normal earthing to protective multiple earthing it is only necessary to connect the earth-continuity conductor to the neutral on the live side of the switch if one is used, or to the link if there is no switch in the neutral. Certain other precautions which are desirable are dealt with in a later Section. If the house wiring is carried out with 2-core tough-rubber-sheathed cable, then a separate earth-continuity conductor would have to be run. In new installations a 3-core cable or one having a special earthing core would be used.

With this arrangement, if the neutral conductor breaks inside the installation the appliance does not operate and no dangerous potential-rise takes place on frameworks. This is shown in Fig. 8, which also shows the path of the fault current in the event of a breakdown of insulation occurring on the appliance. From this diagram it will be clear that the elimination of neutral fuses in the installation is not essential, but on the other hand they serve no useful purpose, and discontinuance of their use would effect a saving in cost. As in the usual method of earthing, one is dependent on the earth conductor being continuous and of low resistance. If protective multiple earthing is used the occasions on which this conductor has to carry a substantial current will increase since, as already shown, in many present installations the earth resistance is too high to enable any appreciable current to flow, and in this event defec-

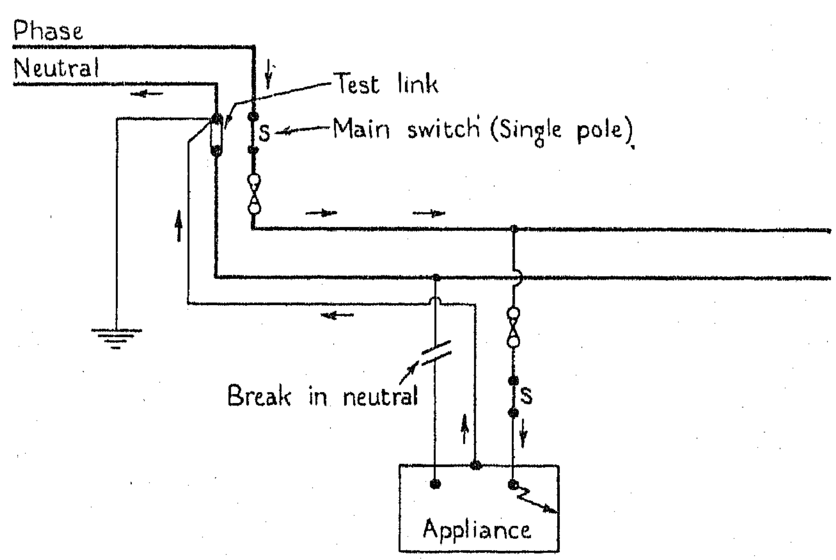


Fig. 8.—Broken neutral inside the consumer's premises.

tive earth-continuity conductors are likely to be more often found. One of the recommendations made later is that before an installation is connected for protective multiple earthing the resistance of this conductor should be reduced to 0·5 ohm—which resistance should be measured with a substantial current flowing.

(*iii*) *Danger of a Broken Neutral Service Conductor.*

Having shown that no danger arises if the neutral breaks inside the installation, the question of a break in

the neutral between the consumers' terminals and the substation will now be dealt with. Fig. 9 shows a broken neutral service conductor. In this case all the frameworks of earthed appliances within the house will be at a potential above earth of v, where

$$v=E\left\{\frac{R_E}{\dfrac{R_AR_BR_C\ldots}{R_BR_CR_D\ldots+R_AR_CR_D\ldots+R_AR_BR_D+\ldots}+R_E}\right\}$$

where

E = supply voltage.
R_E = earth resistance of electrode at consumers' premises.
R_A, R_B, R_C, ... = resistance between terminals of all appliances in the installation which are switched on.

The term

$$\frac{R_AR_BR_C\ldots}{R_BR_CR_D\ldots+R_AR_CR_D\ldots+R_AR_BR_D+\ldots}$$

is the total parallel resistance connected across the mains and may be represented by R; then

$$v=\frac{R_E}{R+R_E}E$$

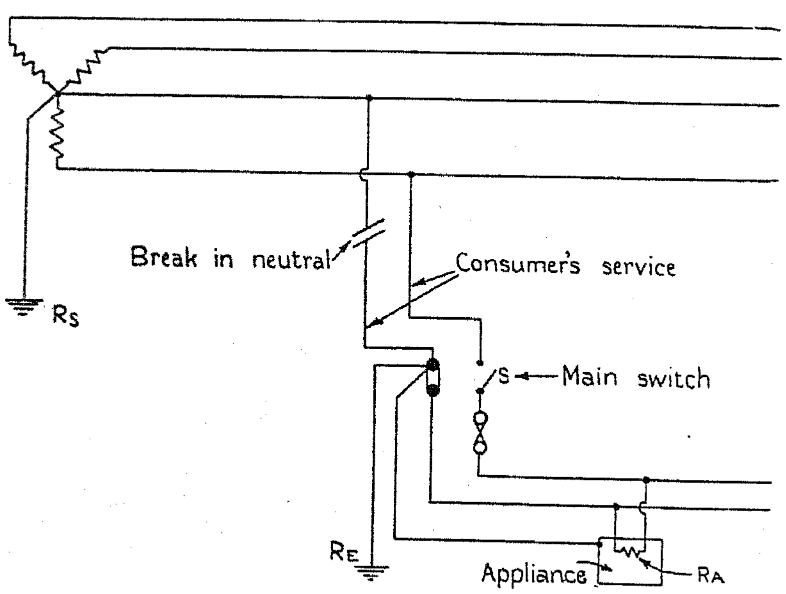


Fig. 9.—Broken neutral service conductor.

Previous details have shown that for rural areas R_E may vary from less than 1 ohm to over 3 000 ohms, but for pipe or rod electrodes there should not be much difficulty in the majority of places of keeping the values between 10 and 100 ohms (70 % of the pipes and rods tested were within this range). In Fig. 10 curves are shown relating the voltage above earth of apparatus frameworks for various values of earth resistance at the consumers' premises and of loads switched on at the time of the fracture of the neutral service. At 10 ohms it will be seen that the rise of voltage is 36 volts with 1 kW switched on; at 100 ohms the value is 152 volts. (This assumes that the resistance at the substation is zero.)

At the larger values of connected load and earth resistance a dangerous voltage may occur on apparatus, but the important point which the curves bring out is that the switching-on of a small load does not represent a danger. It has frequently been stated in criticisms of protective multiple earthing that if the neutral is broken the switching-on of a single lamp raises all metal-work to the voltage of the live line. This is clearly not the case unless there is no connection with the earth on the remote side of the break; even with 1 000 ohms resistance to earth the voltage is only 120 when a 60-watt lamp is switched on.

(iv) Danger of a Broken Neutral Distributor.

In the case of the neutral distributor breaking without the phase wire similar conditions prevail in respect to

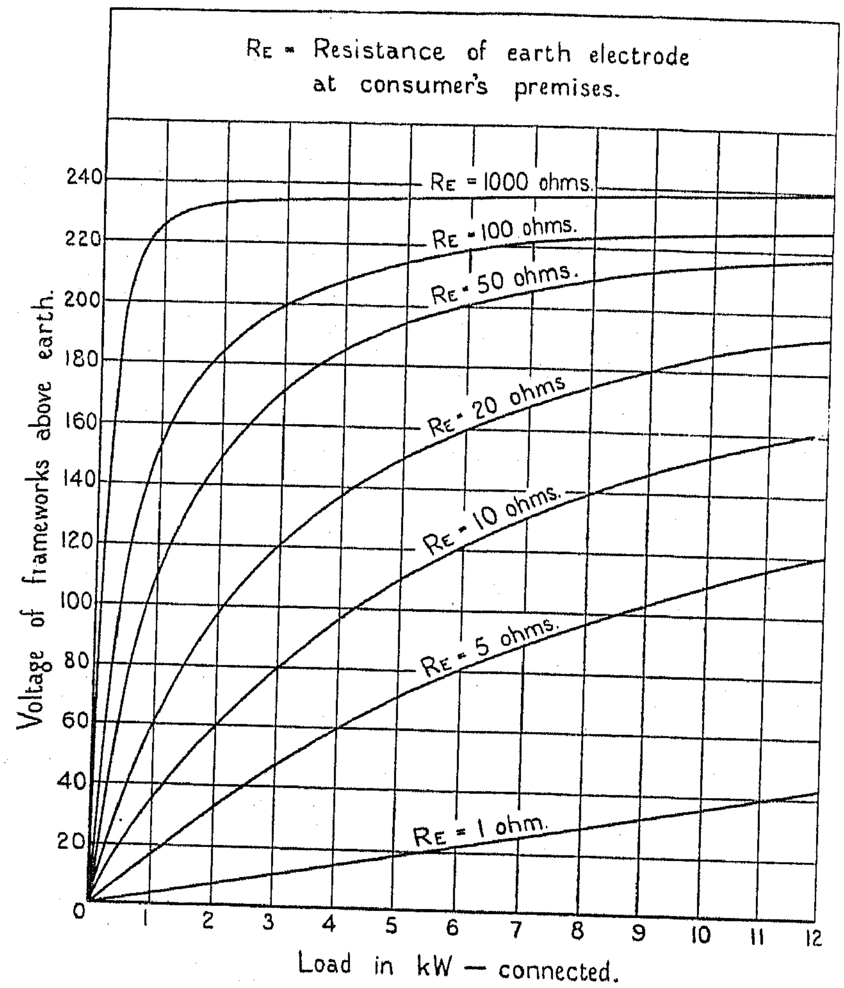


Fig. 10.—Voltage above earth of protected frameworks for various values of earth resistance and installed capacity when a break occurs in a neutral service conductor.

the voltage-rise of frameworks, except that this takes place at all consumers' premises. The actual voltage-rise is again controlled by the total load connected when the fracture occurs and the parallel resistance to earth of the electrodes at the consumers' premises, but in this case the relative values of the earth resistances of the neutral conductor on the two sides of the break must be taken into account.

The diagram at the top of Fig. 11 shows the conditions when a neutral distributor breaks. All the earth electrodes on the sections between the substation and the break may be regarded as being in parallel and having a resistance of R_1 ohms, and those on the side of the break remote from the substation are shown as having a parallel resistance of R_2 ohms. It is noteworthy that a broken neutral distributor does not result in interruption of the supply, though a drop in voltage will occur due to the resistances R_1 and R_2 in series.

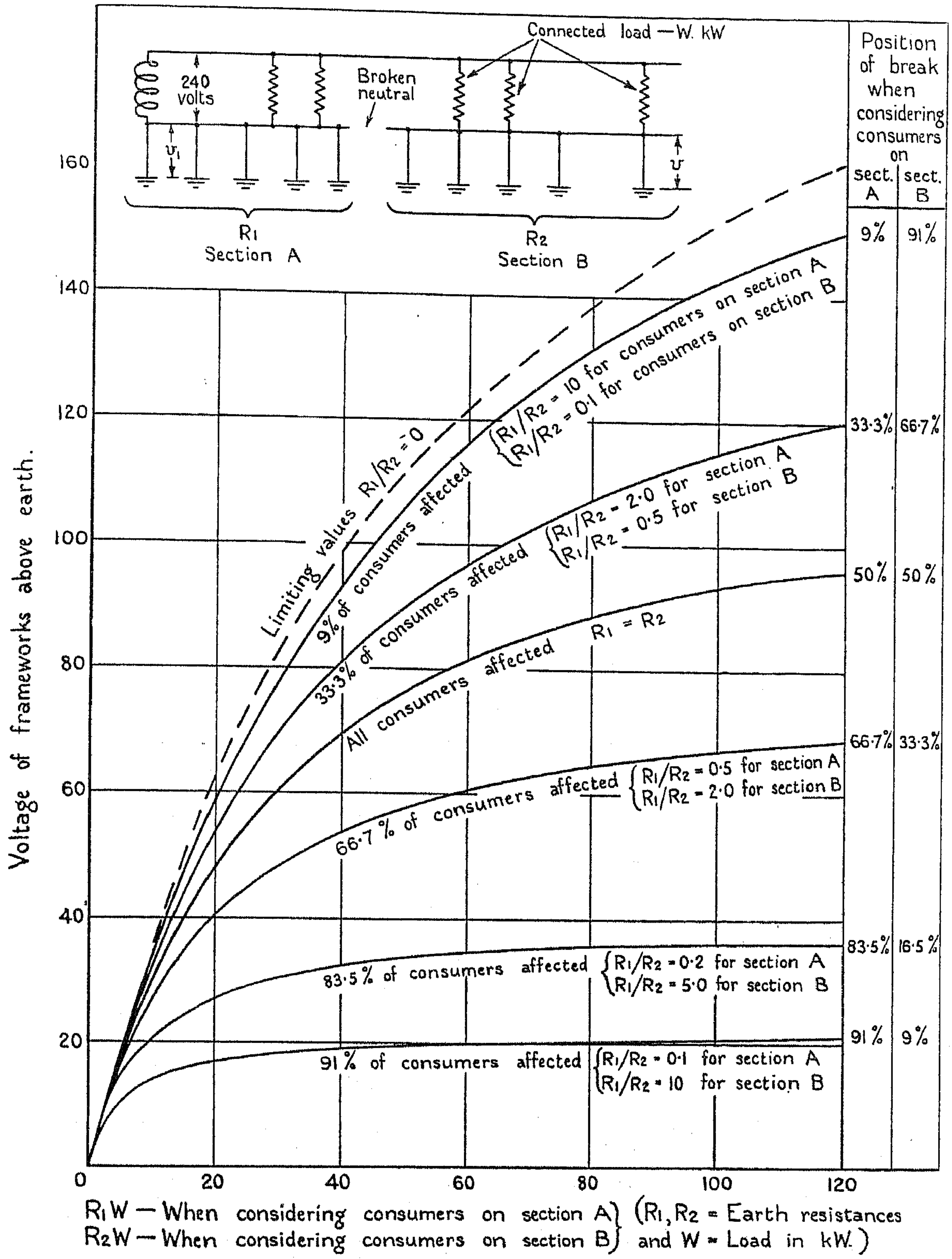


Fig. 11.—Voltage above earth of protected frameworks for various values of earth resistance and installed capacity when a break occurs in a neutral distributor.

Let

R = resistance of connected load on remote side of break.

W = kW capacity of connected load.

V = supply voltage = 240.

v = voltage of disconnected neutral (and frameworks) with respect to earth.

v_1 = voltage of sound section of neutral (and connected frameworks) with respect to earth.

Then
$$v = \frac{R_2}{R_1 + R_2 + R}V$$
$$= \frac{V}{1 + R_1/R_2 + R/R_2}$$

Now
$$R = V^2/1\,000W = 57{\cdot}6/W$$

and
$$V = 240$$

therefore
$$v = \frac{240}{1 + R_1/R_2 + 57{\cdot}6/(WR_2)}$$

Similarly
$$v_1 = \frac{240}{1 + R_2/R_1 + 57{\cdot}6/(WR_1)}$$

It should be noted that a voltage-rise takes place on the sound as well as the disconnected section of the neutral, although attention has only been directed to the latter in the past. The voltage-rise of the former will be considered first.

From the equations given, curves relating v and v_1 to (R_2W) and (R_1W) for various values of R_1/R_2 are plotted in Fig. 10. The limiting upper value of v occurs when $R_1/R_2 \to 0$, i.e. when the break occurs at the far end of

the distributor. Values above 30 volts are obtained when $R_2W > 8$, corresponding to a 1-kW fire and 8 ohms earth resistance or a 100-watt lamp and 80 ohms. As the distance from the extreme end increases, the voltage-rise for any given value of R_2W decreases, but the number of consumers on the remote side of the break in the neutral increases. If we may assume a symmetrical loading and equal earth resistances, at one-third of the distance back to the substation (i.e. when $R_1/R_2 = 0 \cdot 5$) 30 volts is experienced on metal-work when $R_2W > 10$, and 60 volts when $R_2W > 24$. If the break is half-way between the substation and the end of the distributor $R_2W = 15$ gives 30 volts, and $R_2W = 30$ gives 60 volts. As the break approaches the substation the danger to those on the disconnected neutral rapidly diminishes; thus at one-sixth of the length of the distributor away the maximum voltage which can be experienced by all the consumers on the remaining five-sixths of the distributor does not exceed 40 even when the product $R_2W = 1\,000$—corresponding to, say, 10 ohms and 100 kW.

On the substation side of the break the complement of the above results exists, that is the voltage experienced by the consumers is greatest when the break is near the substation and least when it is remote from it. If the break occurs at D % of the total distance from the substation the voltage-rise on the sound neutral is the same as that on the disconnected neutral when the break occurs at D % of the total distance from the end of the distributor, or $(100 - D)$ % from the substation, for the same connected load.

If the total danger may be expressed as the sum of the products of the number of consumers connected on the two sides of the break multiplied by the respective rises of voltage of the frameworks, it will be apparent that if the break occurs at either end of the line the danger is zero, since in one product the number of consumers is nil and in the other the voltage is negligible. The maximum danger, in a symmetrically loaded system with a single distributor, occurs when the break takes place at about 30 % to 40 % of the distance between the substation and the end of the distributor.

The magnitude of the danger is dependent on R_1W and R_2W, and since W is beyond control it is desirable that R_1 and R_2 should be kept as low as possible. This means that the general resistance of the neutral to earth should be low throughout the system so that wherever a break in the neutral occurs the product R_1W or R_2W is small—inspection of Fig. 10 will make this immediately clear.

This analysis has been based on a single distributor, but clearly with a network of distributors the current from the broken section of neutral returns to the neutral point through all the earth connections on the system. R_1 may thus be very small in a large network wherever the break occurs. This makes the position worse for the consumers connected on the remote side of the break, but reduces the voltage on frameworks connected to the sound neutrals.

In considering the dangers arising from a broken neutral it is important to note that the fracture of a neutral distributor without the phase wire is, in this country, a very rare occurrence. In fact such a case has never been brought to the notice of the E.R.A., and details of any that has occurred would be welcomed. The fracture of a consumers' neutral service without the phase wire is somewhat more likely to occur since the conductor is of smaller size than the distributors, and corrosion of the clamps at either end might conceivably produce such a breakdown. The important point which should, however, be fully appreciated is that even if a neutral distributor or service did break the risk of shock would be less than with ordinary earthing.* Furthermore, there is the important point that if a neutral distributor broke, apparatus would cease to function correctly owing to low voltage, and steps would be taken to have it rectified at once, but no such indication is given when a fault occurs on apparatus earthed normally. If, due to a low earth resistance, apparatus continues to function correctly after the fracture of a neutral service, then it cannot be in a dangerous condition since the major voltage-drop will take place across the winding of the appliance and only a small drop across the earth electrode.

It is of some significance to point out that very dangerous conditions may occur, due to unbalanced loading, on any three-wire single-phase or four-wire three-phase system if the neutral breaks. The resulting excess voltage on the lightly loaded side could cause the burning out of all the apparatus; yet this objection to a broken neutral is never advanced as a reason for not using these systems, for the simple reason that the fracture of the neutral conductor alone is practically unknown.

The relative safety of the present method of earthing in rural areas, and the safety which would be obtained by the use of protective multiple earthing, is a matter of some considerable importance, and an attempt will be made to express it numerically.

Let

N = number of faults (which are not cleared) occurring at each consumer's premises over a given period of time, using normal earthing.

n = number of consumers.

t = time for which apparatus remains in a dangerous condition, using normal earthing.

N_1 = number of occasions per consumer on which a fracture of a neutral service takes place over the same period of time, using protective multiple earthing.

N_2 = number of occasions on which a fracture of the neutral distributor takes places in the same conditions.

t_1 = time for which apparatus remains alive in both cases.

Let us consider that the danger of either system may be expressed as the product of the number of consumers, the time of exposure, and the number of faults per consumer,† then for normally earthed systems the danger may be represented by $0 \cdot 5\ Nnt$ if we consider that half the faults do not blow the fuse, and for the systems using protective multiple earthing by $(N_1nt_1 + N_2nt_1)$.

* The danger is less since, with normal ineffective earthing, full voltage occurs on the metal-work if the fuse does not blow; with protective multiple earthing only a proportion of the full voltage is attained by the metal-work since part of the drop occurs in the element or winding.

† This comparison neglects the fact that the voltage on the metal-work is less with the protective multiple earthing system than with the ordinary system.

$$\frac{\text{Danger in system using ordinary earthing}}{\text{Danger in system using protective multiple earthing}} = \frac{0\cdot 5\, Nnt}{N_1 nt_1 + N_2 nt_1}$$

$$= \frac{0\cdot 5\, Nt}{t_1(N_1 + N_2)}$$

To obtain some idea of the numerical value of this ratio let us assume that $N = 1$ fault per annum or 10 faults per 10 years. In this period we might assume that the neutral distributor would break once and the neutral service would break at 10 % of consumers' premises, then $N/(N_1 + N_2) = 10/(1 + 0\cdot 1) = 9$ (approx.). It is not easy to give a figure for the ratio t/t_1, since although an appliance may be alive for a considerable time under ordinary earthing conditions, once the fact became known it could no longer be regarded as such a serious source of danger. Considering, however, that the fault does not reveal itself until a shock is obtained, whereas if the neutral breaks the fault is revealed by the defective operation of apparatus without a shock necessarily being obtained, and moreover that if the distributor breaks any one consumer is sufficient to reveal the existence of the danger and have it rectified, we may safely take t/t_1 as 2 at the very least. On this basis we find that the system with protective multiple earthing is 9 times as safe as the system with normal earthing in which the earth resistances are of the same order as those determined in the measurements cited previously.

This figure may be regarded as very high and is admittedly only based on estimates. To place the number of faults per consumer at one per annum may be considered high, but the ratio $N/(N_1 + N_2)$ cannot be much less than 9. If in the extreme it may be taken as 5 there is still a large margin of safety in favour of the protective multiple earthing scheme.

Against this must be set the disadvantage that any voltage-rise of the neutral is impressed on the protected metal-work, and with long distributors it is conceivable that this might be sufficiently high to constitute a danger. This possibility has been experimentally investigated, and the results are described in the next Section. In this Section also consideration is given to the possibility of interference with the operation of Post Office telephone systems due to proximity between the telephone and power earth electrodes at the consumers' premises.

Another disadvantage is that it is not possible with protective multiple earthing to check the existence of earth faults on the phase wires by observing the earth current during light-load periods, since a large earth current will always be flowing.

There is also the possibility that a short-circuit between phase wire and neutral would not enable sufficient current to flow to blow the fuses. In this event a dangerous potential might exist on metal-work connected to the neutral. Disregarding the question of whether a system can be considered as adequately protected if the line impedance is so great that a dead short-circuit on the distributors will not blow the section fuse, let us consider the magnitude of the voltage-rise which can occur. It is shown later that by suitable arrangement of the multiple earthing points the voltage-rise of the neutral above earth may be reduced to 50 % of the total neutral voltage-drop. It is also shown that this drop is less than half the total line drop. (In one test it was as low as one-third.) Taking the voltage at the transformer terminals as 220 (allowing 20 volts drop due to the abnormal load) the voltage of the metal-work above earth at the extreme end of the distributor may be as low as 37 volts. Provided certain precautions are observed in effecting the multiple earthing it need in no case exceed 60 volts near the substation and at the extreme end of the distributor. Midway between these points it would be zero, and between the centre and the extremities the value would vary in proportion to the distance. It cannot be denied that the circumstances may be dangerous, but the danger is much less than is generally supposed.

In order to protect against the danger of a voltage-rise of the neutral conductor in systems using protective multiple earthing, the substation leakage circuit breaker referred to in Section (4) (*a*) (ii) may be used. This operates in the same manner as those used in domestic installations, except that instead of the trip coil being connected between the framework and earth it is connected between the neutral and earth—care being taken to ensure that the trip-coil earth is outside the resistance area of the main earth (though it has been suggested that control of the tripping voltage may be obtained by bringing the auxiliary earth within the resistance area of the main earth and varying their distance apart). Under fault conditions the potential of the neutral point rises with respect to earth by an amount equal to the product of its resistance and the current flowing, and the trip coil will operate if this exceeds a predetermined value.

It will be noted, therefore, that there is a clear difference between the method of using leakage circuit breakers at consumers' premises and at the substation. In the former case the trip coil is usually connected between metal-work and earth, and this provides the only earth connection. In the latter case the trip coil is connected in parallel with the main neutral-point earth, and therefore carries only a small proportion of the total fault current. There is thus discrimination between the substation and consumers' circuit breakers.*

Overload protection by means of bimetallic strip thermal releases is sometimes incorporated with the circuit breakers to eliminate the necessity for fuses, and these are fitted in the neutral wire as well as in the phase wires. The setting of the neutral release is about 25 % of that of the phase wires, and thus much better protection is provided against earth faults or phase-to-neutral short-circuits than is possible with fuses, since these cannot be used in a neutral conductor at the substation. Supplementary contacts are sometimes fitted to the trip-coil circuit to ensure that this is opened when the switch is operated—the object being to protect the trip coil against a fault on the switchgear or transformer which would not be cleared by the operation of the leakage switch. A time-delay action is also sometimes used to prevent the circuit breaker operating on voltage-rises of short duration.

* If the consumers' leakage circuit-breaker is connected to earth in parallel with a direct earth connection, discrimination will not be so readily obtained.

(5) PRACTICAL TESTS ON EARTH-LEAKAGE CIRCUIT BREAKERS

As shown earlier, one of the objections to earth-leakage circuit breakers is that if the earth resistance is sufficiently high the voltage required to trip the breaker may be appreciably above the safe value of 30 volts. In order to investigate this under practical conditions, Mr. E. Fawssett has conducted tests, in association with Mr. J. S. Pickles, in the supply area of the electricity department of the County Council of Dumfries.

On account of the difficulty experienced in obtaining satisfactory earth resistances, earth-leakage circuit breakers have been in use by this undertaking over a period of about 2 years, and at present about 700 are installed. Beyond routine flashing tests they have received no attention. Investigations were made on 37 circuit breakers selected at random, the procedure being to connect a potentiometer rheostat across the supply and gradually increase the voltage applied to the frame of the protected appliance until the breaker tripped. The operating voltage was measured by means of a high-resistance voltmeter connected between the framework and true earth. The results are shown in Table 1.

These results show that of the circuit breakers examined, without overhaul or any sort of preliminary precaution, 30 % tripped at 30 volts or less, 50 % at not more than 40 volts, a further 40 % between 40 and 85 volts, and the remaining 10 % (4 breakers) when first tested operated at values up to 210 volts. By adjustment on site two of those operating at 200 volts were brought down to 85 volts and 75 volts. It is important to note the large proportion of circuit breakers which were in such a condition when the test was applied as to be completely effective in preventing danger, and also to note that *all* are effective in cutting off a direct fault, which would remain on with ordinary earthing in every case. It will be observed that the earth resistances in this area are distinctly high—the average of 30 measurements being 500 ohms. The values are higher on the average than those at the four villages used for the multiple earthing tests.

The results indicate clearly that the leakage circuit breakers effect a substantial improvement in the protection of consumers in an area where protection by ordinary earthing is practically impossible. In many cases the operating voltages were too high to ensure complete protection, but a number of the circuit breakers were of an early type and with the improved types now available and the development of technique there is good reason to expect better results in the future.

(6) PRACTICAL TESTS ON PROTECTIVE MULTIPLE EARTHING

Practical tests have been carried out at three villages chosen as being those in which the maximum interference with the telephone system, or the maximum rise of potential of the neutral conductor, might occur. In each case a heavy load was applied at the end of long distributors with the object of finding the maximum rise of potential of the neutral conductor with respect to earth, and whether any interference occurred with the operation of Post Office telephone systems.

In order to mask the effect of small loads taken by

Table 1

DUMFRIES TESTS—VOLTAGE REQUIRED TO OPERATE EARTH-LEAKAGE CIRCUIT BREAKERS.

No.	District	Earth resistance	Tripping voltage
1	Heathhall	—	150
2	Holywood	110	85
3	Holywood	280	80
4	Holywood	110	65
5	Holywood	340	200
5	After adjustment		85
6	Locharbriggs	—	50
7	Locharbriggs	780	200
7	After adjustment		75
8	Collin	300	50
9	Collin	275	28
10	Collin	125	40
10	After adjustment		36
11	Collin	650	45
12	Dalton	23·5	16
13	Dalton	70	16
14	Hightae	1 250	55
15	Hightae	1 460	65
16	Torthorwald	460	32
17	Dunscore	1 175	84
18	Dunscore	100	20
19	Dunscore	66	20
20	Dunscore	13	30
21	Dunscore	1 200	210
22	Beattock	160	30
23	Beattock	100	29
24	Beattock	130	15
25	Beattock	450	35
26	Beattock	450	40
27	Templand	300	28
28	Templand	500	57·5
29	Templand	>600	32·5
30	Templand	>600	58
31	Templand	260	50
32	Millhouse Bridge	600	48
33	Millhouse Bridge	240	12·5
34	Millhouse Bridge	400	40
35	Wamphray	500	48
36	Wamphray	600	40
37	Wamphray	420	55

consumers, larger test loads were generally applied than would actually be used in practice, so that the rises of potential experienced exceed what might be expected in normal conditions of operation. They do not necessarily exceed the values which may occur for a short period prior to the blowing of a fuse.

The principal details relating to the three systems tested are given in Table 2.

In each case test loads were applied at the end of the longest distributor. In the case of village "F" two test sites were used and loads of various magnitudes applied at both sites; in the other cases only one test site was used. The load current, neutral current, and earth current, were determined at the test site and substation, and in addition the neutral current was measured at various points in the system. The voltage of the neutral conductor with respect to earth was also measured at as many points as possible.

In addition to steady-load conditions, tests were made to simulate the conditions which exist when a fuse blows. According to the I.E.E. Regulations* a fuse must blow within one minute on 100 % overload. For shorter periods than this it may be taken approximately that the time of blowing is inversely proportional to the square of the current. Thus a 15-ampere fuse must blow within one minute at 30 amperes and may carry as much as 60 amperes for 15 seconds. Similarly, a 30-ampere fuse may carry 120 amperes for 15 seconds and 200 amperes for 5 seconds. In the case of villages "A" and "E" the line was practically short-circuited through a fuse and the maximum currents obtained for about 5 seconds were 158 amperes at "A" and 130 amperes at "E."

Interference with the operations of telephone systems only occurs where C.B.S. No. 1 type exchanges are used, and takes the form of bell tinkling and false ringing. This is due to the subscribers' telephone earth electrode being too near the power-system earth. In order to test whether this trouble would arise with a multiple-earthed system, special subscribers' earths were buried at a distance from the power earths which was regarded as the closest proximity that need occur in practice. The voltage picked up by these plates was measured by extending to the sites single-wire pilot lines connected to the exchange earth-plate system. The induced noise on subscribers' circuits was also measured by means of a psophometer.

* Regulation 1333 (A), 10th Edition.

Tests were in general made under the following conditions:—

(a) Normal, i.e. neutral earthed at the substation only.
(b) Neutral earthed at a small number of special low-resistance electrodes specially installed, and at the substation.
(c) Neutral earthed at consumers' premises and at the substation.

In addition, variations were introduced according to the circumstances.

The principal test results are shown in Table 3 for the three villages.*

In col. 5 for village "F" two figures are given for the phase current; the upper one refers to the red phase and the lower one to the blue. Where two figures are given in other columns the upper one refers to site 1 and the lower to site 2—the two places at the ends of distributors where the test loads were applied. At this village it was not convenient to earth the neutral at the premises of more than 18 consumers, and in this case the maximum voltage of the neutral above earth was 16 volts at site 2. This was reduced to 4·2 volts by connecting the static balancer. The load was approximately the same in tests 9 and 12 and it will be noticed from col. 16 that the voltage-drop in the neutral is only slightly less in the second case than in the first. The reduction of the maximum voltage of the neutral at the test site from 22·5 to 16·0 is due to a shift of the neutral point which increases the voltage of the neutral at the substation from 0·4 to 5·1.

For village "A" the results of four tests are shown for the conditions indicated in col. 4. The maximum voltage of the neutral with respect to earth was 42·6 volts, and this occurred with a fusing current of 158 amperes. Under steady-current conditions the maximum value with multiple earthing was 28·8, the load current being 46 amperes at the test site, and the total phase current at the substation 79·8 amperes.

The voltage-rise of the neutral conductor for all the tests at "A" is shown diagrammatically in Fig. 12. Actual values of voltage above earth were obtained in most tests at four points, though in a few at site P the values were above the range of the instrument used. Between the test points only a straight line can be shown,

* Full details of the tests are given in E.R.A. Report Ref. F/T102: "The Safety of Consumers in Rural Areas," by H. G. Taylor.

Table 2

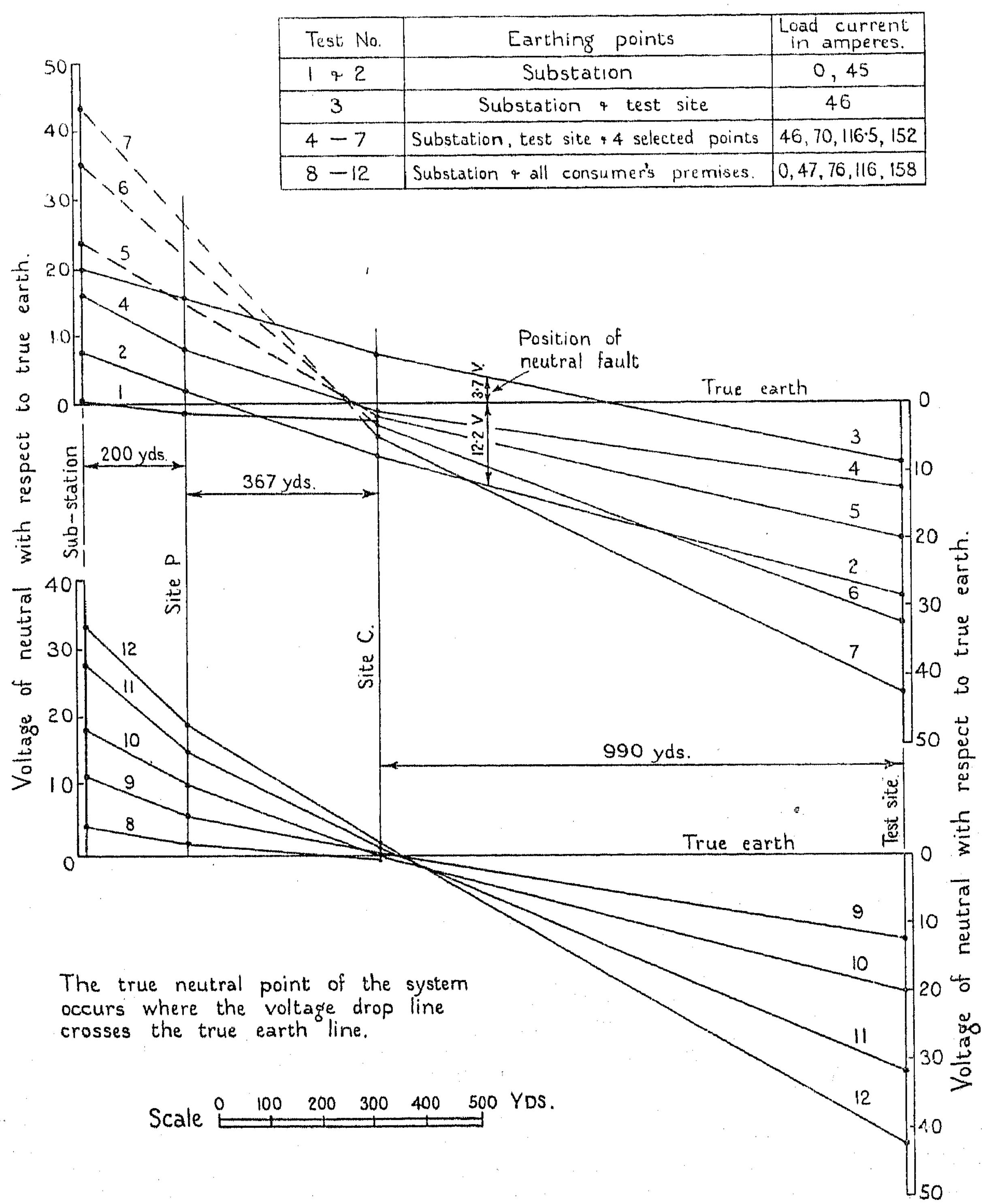
Reference letter of village	Locality	Type of soil	Type of supply	Number of consumers	Length of longest distributor	Conductor sizes
		Shale with a thin overlay of:—			yards	sq. in.
F	Northumberland	Sand	500-volt, 3-wire, 1-phase	150	1 050	0·05 and 0·025
A	Berkshire	Clay	230-volt, 2-wire, 1-phase	70	1 557	0·06
E	Sussex	Clay	400/230-volt, 4-wire, 3-phase	46	2 084	0·1 and 0·05

Table 3.—PRINCIPAL RESULTS OF TESTS ON PROTECTIVE MULTIPLE EARTHING

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Substation			Principal test site			Phase voltage			Voltage of neutral with respect to earth					
Village reference	Date of test	Test No.	Conditions	Phase current	Neutral current	Earth current	Phase current	Neutral current	Earth current	At sub-station	At test site	Total line voltage-drop	At sub-station	At test site	Neutral voltage-drop	Neutral drop as percentage of line drop	Voltage-drop per ampere of load current	Maximum voltage in P.O. pilots
	8.10.35 and 9.10.35	9	Neutral earthed at substation.. ..	76R 18B	58	0	38·4 20·5	38·4 20·5	0 0	254	—	—	0·4	21·1 22·5	21·5 22·9	—	—	0 0
F		12	Neutral earthed at substation and at 18 consumers' premises	69R 5B	57·4	6·6	39·1 20·7	39·1 20·5	0·05 0·19	255	—	—	5·1	14·7 16·0	19·8 21·1	—	—	0·3 0·8
		13	Ditto, but with static balancer at site 2 connected	57R 20B	33·2	3·8	39·4 23·1	39·4 23·1	0·05 0·03	256	—	—	2·9	15·2 4·2	18·1 7·1	—	—	0·2 0·3
	30.1.36	2	Neutral earthed at substation.. ..	63	59	4·0	45	45	0	235	164	71	7·3	28·5	35·8	50·4	1·16	0·09
	30.1.36	4	Neutral earthed at substation, test site, and 4 other selected points	79·8	70·8	9·0	46	30·8	15·2	234	167	67	16·3	12·5	28·8	43·1	1·06	3·39
A	31.1.36	9	Neutral earthed at substation and all consumers' premises	66	59·7	6·3	47	47	0	232	169	63	11·5	12·3	23·8	37·5	1·10	—
	31.1.36	12	Neutral earthed at substation and all consumers' premises	>100	>82	18·4	158	158	0	222	8	214	33·6	42·6	76·2	35·7	1·27	—
	18.2.36	2	Neutral earthed at substation.. ..	56	46	4·1	39	39	0	233	182	51	12·3	18·0	30·3	59·5	1·09	0·40
	18.2.36	3	Neutral earthed at substation, selected points, and to rod at test site	52	44	4·9	49	47·7	1·3	232	170	62	14·7	20·0	34·7	56·1	1·20	1·4
	18.2.36	6	Neutral earthed at substation, selected points, and to rod at test site	140	112	15·2	134·7	131	3·7	223	<20	>203	45·5	58	103·5	<51·0	1·48	—
E	18.2.36	7	Neutral earthed at substation and to rod at test site	65	49	6·1	55·5	54	1·5	232	156	76	18·3	23	41·3	54·5	1·27	0·5
	18.2.36	8	Neutral earthed at substation and to water pipes at test site	67	50·5	9·5	57·3	44·3	13·0	233	158	75	28·5	4·5	33·0	44	1·20	3·1
	19.2.36	10	Neutral earthed at substation, all consumers' premises, and to water mains at test site	72	56	6·8	51·5	33	18·5	231	160	71	19·3	7·1	26·4	37·2	1·14	5·2
	19.2.36	11	Neutral earthed at substation, all consumers' premises, and to rod at test site	68	49·5	5·0	53·4	52	1·4	231	153	78	15·0	22	37·0	47·5	1·28	2·2
	19.2.36	14	Neutral earthed at substation, all consumers' premises, and to rod at test site	139	121	13·5	129·5	126	3·5	221	8	213	40·4	56	96·4	45·2	1·58	4·0
E	19.2.36	15	Neutral earthed at substation, all consumers' premises, selected points, and to water mains at test site	64	57	5·1	51·5	32	19·5	233	164	69	15·4	7·4	22·8	33·1	1·21	5·7

but it will be appreciated that on account of consumers' loads there should be a succession of straight lines lying approximately on a curve. The true neutral of the distribution system moves about between the substation and the test site in accordance with the loading and the position of the earthing points. In test 1 it will be seen to be practically at the substation. In test 2 it is at a point about 270 yards from the substation, and in test 3 system tends to be safest where the load concentration is highest, and the maximum voltage difference between the neutral and earth is less than the total voltage-drop in the neutral and may be as low as 50 % of it.

For a distribution system of the type existing at "A" it may be considered that 46 amperes is greater than would normally occur at the end of the long distributor, since with this current the total drop in volts with only



Test No.	Earthing points	Load current in amperes.
1 + 2	Substation	0, 45
3	Substation + test site	46
4 — 7	Substation, test site + 4 selected points	46, 70, 116·5, 152
8 — 12	Substation + all consumer's premises.	0, 47, 76, 116, 158

Fig. 12.—Voltage-rise of the neutral conductor at " A."

it is 1 000 yards away. In this test there were only two deliberate earths on the system—one at the substation, of 1·82 ohms resistance, and one at the test site, of 0·88 ohm resistance. The true neutral point is therefore nearer the latter than the former.

In tests 4 to 7 the neutral conductor was earthed at six points, which had the effect of moving the neutral point to the centre of the village. It will be seen that all the voltage-drop lines cross the true earth line at about the same point. The value of this effect is that the one earth is about 40, that is 17 % of the declared voltage. When the load current was 46 amperes and the neutral was connected to earth at the test site its maximum voltage above earth was 20; with a number of earths on the neutral it was 16; and with the neutral earthed at all consumers' premises the value was 11·5 volts. With a load current which would bring the voltage-drop within the statutory limit the voltage-rise of the neutral would be quite negligible as regards shock risk. In order to determine the voltage-rise of the

neutral under normal operating conditions, a recording voltmeter was connected between the neutral conductor and earth for a period of 12 days subsequent to the tests. The maximum rise recorded was 13 volts, which confirms the view that the tests imposed more stringent conditions than would occur in practice. A similar test at village "F" gave a value of 9 volts over a period of 7 days.

Examination of col. 17 of Table 3 will show that the neutral voltage-drop expressed as a percentage of the total line voltage-drop is less with multiple earthing than with single-point earthing—the proportion falling from about 50 % to 43 % with selected earths and 36 % with earths at all consumers' premises. On the other hand, the total line drop does not vary very much, as may be seen from col. 18, and therefore the voltage-drop on the phase wire must increase with multiple earthing.

The same effect was observed at village "E," where the neutral drop fell from 59·5 % of the line drop to 33·1 %, but at the same time the line voltage-drop per ampere for the various earthing arrangements did not change very much.

The combination of reduced neutral voltage-drop with the movement of the neutral point away from the sub-station is of great advantage from the aspect of voltage-rise of metal-work connected to the neutral, but the tests show that a reduction of line voltage-drop cannot

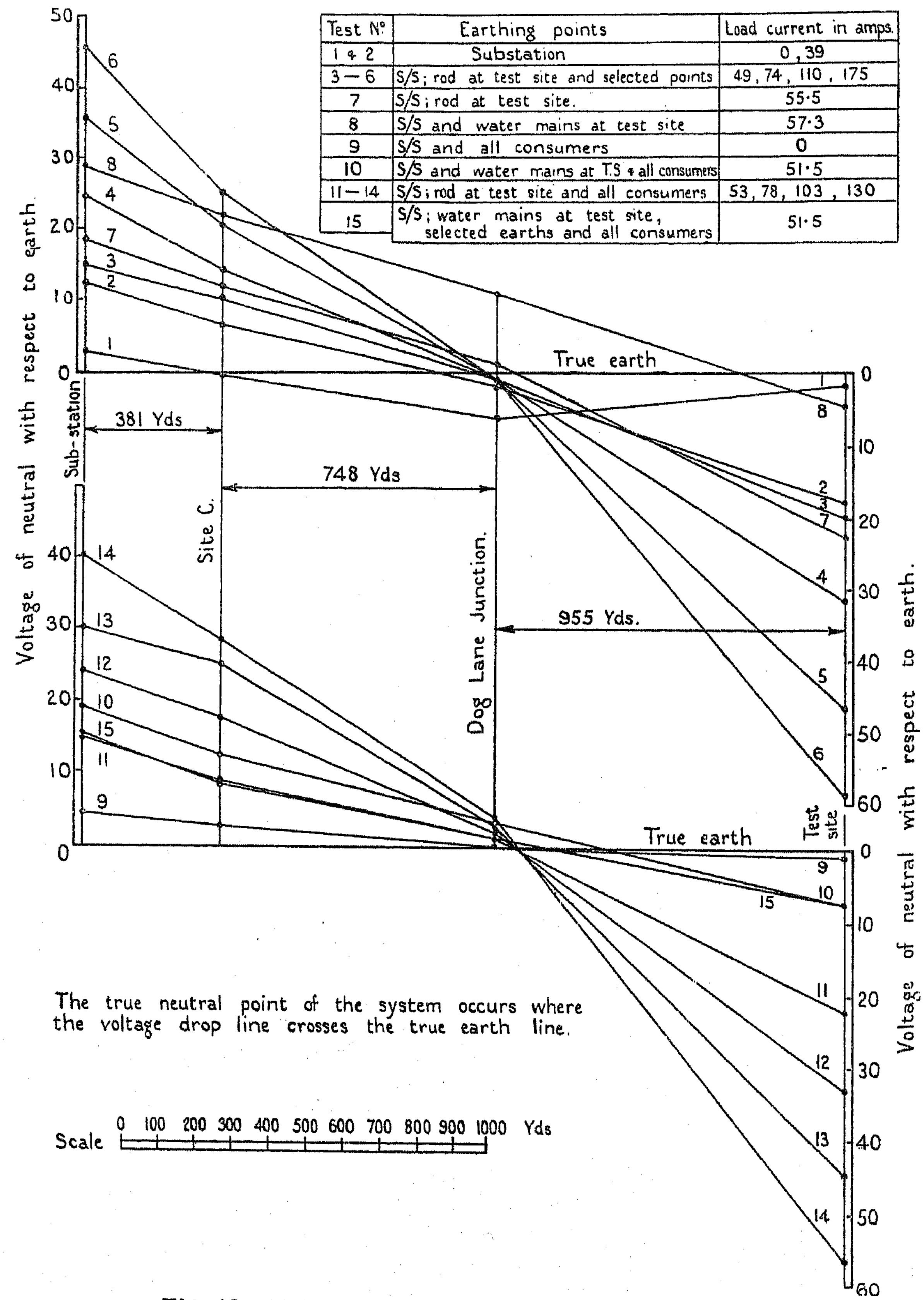


Fig. 13.—Voltage-rise of the neutral conductor at "E."

be claimed as one of the advantages of protective multiple earthing.

In the tests at village "E" it was possible to make greater variations in the earthing arrangements than elsewhere, since a small water system having a resistance of only 0·35 ohm existed on the test site; as an alternative a rod electrode was used having a resistance of 15·5 ohms. In test 15 the maximum possible number of earth connections was made on the system—an arrangement which was not used elsewhere. All consumers' earths were connected to the neutral (see Fig. 1 for values), and also five selected earths (three of which were specially made) were used, their values being 2·95, 1·5, 1·8, 2·0, and 1·1 ohms. In this test the voltage-rise of the neutral at 51·5 amperes load current was reduced to 7·4 volts at the end of the longest distributor and 15·4 volts at the substation. The neutral drop was thus 22·80 volts and the total line drop was 69 volts.

The voltage-rise of the neutral for all the tests at "E" is shown diagrammatically in Fig. 13. The upper diagram shows the tests with and without selected earths, and the lower diagram the tests with the neutral earthed at consumers' premises. As shown in the tests at "A," the true neutral point of the system moves about according to the position and magnitude of the earths and the distribution of loads. In test 1 it is at about 350 yards from the substation (this is due to an earth fault on the neutral). In test 2 a load of 39 amperes was applied at the test site, and the neutral moved to a point near Dog Lane Junction and remained there for tests 3–6, in which a rod electrode of 15·5 ohms resistance was used at the test site, and selected earths throughout the system, and also for test 7, when the selected earths were removed. The change of resistance from 15·5 ohms to 0·35 ohm at the test site had a very material effect on the position of the neutral point and caused it to move to a position about 250 yards from the extreme end of the distribution system (test 8). As in the tests at "A," it will be noted that the voltage above earth of the neutral when the neutral point is approximately at the middle of the system is roughly one-half the total neutral voltage-drop.

The last column of Table 3 shows the voltage picked up by the P.O. earth plates adjacent to the power-system earths. The maximum value of all the tests was 5·7 volts, which is a value considerably less than that required to cause bell tinkling or false ringing. Listening tests on subscribers' circuits did not reveal any disturbance.

(7) CONCLUSIONS AND RECOMMENDATIONS

(a) *Conclusions on the Practical Tests.*

(i) If the results of measurements made at four villages in different parts of the country may be regarded as typical, in two-thirds of the installations in rural areas fed by overhead networks, where no water mains exist, fuses could not clear an earth fault due to an insulation breakdown on electrical appliances.

(ii) Tests in an area where the earth resistivity is high have shown that earth-leakage circuit breakers, whilst not in all cases functioning at a voltage below the danger limit (viz. 30 volts), have contributed materially towards eliminating the risks of electric shock. Moreover, many of the tests were conducted on early types of circuit breakers, and with the improved types now available and the development of technique there is good reason to expect better results in the future.

(iii) Tests on protective multiple earthing have shown that the voltage-rise of the neutral with respect to earth under quite abnormal conditions of loading does not exceed 30 volts and is therefore not dangerous to human beings, though it may be dangerous to animals.

(iv) When using protective multiple earthing, immediately prior to the blowing of fuses the voltage-rise of the neutral at the end of distributors and near the substation may be 60 volts to earth for a short period.

(v) If the statutory limits of voltage variation are adhered to, the voltage-rise of the neutral will not be dangerous either to human beings or animals.

(vi) The voltages picked up on pilot lines to test earths adjacent to power earths were smaller than would be required to produce false ringing of telephone bells in the C.B.S. No. 1 type of exchange, and listening tests on the telephone lines did not reveal any disturbance.

(vii) Substantial improvement could be effected in existing installations using the present method of earthing by—

(1) Ensuring that an electrode not less than 6 ft. long and not less than $\frac{3}{4}$ in. diameter is always used, and that, if necessary, two are used at least 6 ft. apart.*

(2) Making use of a small water-pipe system, if one exists in the village, as the earth for the neutral, instead of attempting to provide an earth of low resistance at the substation.

(3) Making greater use of a protective earth wire for interconnecting the metal-work in a group of houses, and joining it to earth at a house where a low earth resistance exists.

(viii) The effect of multiple earthing of the neutral is to reduce the voltage-drop in the neutral and earth in parallel to a greater extent than would be expected from the change in resistance; at the same time the voltage-drop in the phase wire is increased.

(ix) Multiple earthing of the neutral does not appreciably improve the voltage regulation.

(b) *Conclusions on Protective Multiple Earthing in General.*

(i) If the connection between the protected metal-work and the (insulated) neutral is made only at the meter board, a fracture of the neutral wire inside the installation does not represent a hazardous condition—the appliance merely ceases to function. If a fault to frame exists, current returns through the neutral wire and the earth-continuity conductor in parallel, and entirely through the latter if a break in the neutral occurs. As this may constitute a fire hazard if it continues for any length of time, it is essential that no fuses or switches should exist in the neutral.

(ii) The voltage-rise of protected metal-work in the

* Further details on methods of obtaining satisfactory earth resistances are given in E.R.A. Report Ref. F/T50: "The Resistance of Earth Electrodes," by P. D. MORGAN and H. G. TAYLOR.

event of a fracture of a neutral service conductor, without the phase wire, is determined by the connected load and the earth resistance at the consumer's premises. For example, on a 240-volt supply, if the resistance is 10 ohms and the load switched on is 1 kW the voltage-rise is 36; if the resistance is 100 ohms the value is 152 volts. The voltage-rise is in no case equal to the full supply voltage, which is the voltage that may occur on metal-work ineffectively earthed in the ordinary way, unless there is no earth at all on the consumer's installation.

(iii) In the event of a break in a neutral distributor without the phase wire all the metal-work on the system rises to a certain voltage with respect to earth, which is determined by the connected load on the remote side of the break from the substation, and the resistance to earth of the neutral on either side; if the break is near the substation the voltage on the frameworks of appliances connected to the sound section of the neutral is higher than that on those connected to the disconnected section; if the break is nearer the end of the distributor than the substation the reverse is the case. From the point of view of general danger the worst position for the break if the system possesses only a single distributor is at 30 % to 40 % of the distance from the substation to the end of the distributor with a uniformly loaded and symmetrically earthed system. The lower the general resistance to earth of the neutral, the less the voltage-rise.

(iv) Comparing the system of protection by earthing which is at present used, with protective multiple earthing, from the point of view of shock risk, it is estimated that the latter system is several times as safe as the former.

(v) With protective multiple earthing, a line-to-neutral fault on the distributor of a 240-volt system would not result in a greater voltage than 60 volts on protected metal-work, provided precautions were taken in effecting the earth connections to ensure that the true neutral point is near the load centre of the system.

(vi) A disadvantage of protective multiple earthing of the neutral is that current returning from an earth fault on the phase wire cannot be distinguished from normal neutral return current.

(vii) Existing installations may readily be converted to the protective multiple earthing system by connecting the earth-continuity conductor to the neutral at the meter board and linking across all neutral fuses.

(*c*) *Recommendations.*

(i) That protective multiple earthing be permitted, subject to compliance with the conditions laid down below.

(ii) That farm installations where animals may come into contact with protective metal-work should be treated differently from house installation, in view of the greater sensitivity of animals to shock than human beings.

(iii) Since small water systems frequently occur at farms it is suggested that such installations only continue to be earthed in the usual way, provided that the total resistance in the earth circuit at any time of the year is low enough to pass two and a half times the current normally carried by the largest fuse on the installation when the voltage applied is equal to the maximum safe value. If this is not possible then earth-leakage circuit breakers should be used on each distinct piece of apparatus and *all* frameworks and metal-work in the installations, liable to become alive, should be protected, where there is danger of animals making contact with the metal-work. The trip-coils should operate at not more than 15 volts.

(iv) If undertakings decide to continue to rely on ordinary earthing the resistance in the total earth circuit should be such that the earth current which will flow at any time of the year, in the event of an earth fault, will be two and a half times the current normally carried by the largest fuse in the installation. If this cannot be ensured then ordinary earthing should not be relied upon, and protective multiple earthing or earth-leakage switches should be used.

(v) If earth-leakage circuit breakers are used, care should be taken to ensure that *all* metal-work throughout the installation which is liable to become alive is protected.

(vi) That a British Standard Specification be prepared for earth-leakage circuit breakers.

(vii) That greater attention be given, in the construction of all electrical appliances, to the provision of a higher standard of insulation.

(*d*) *Proposed Conditions which should be Complied with where Protective Multiple Earthing is Used.*

(i) The size of the neutral distributor should not be less than that of the phase wire, and both conductors should preferably not be less than 0·05 sq. in., in accordance with the circular letter of the Electricity Commissioners to supply authorities, dated April 4th, 1928.

(ii) The neutral should be connected to earth at all consumers' terminals—the earth electrode consisting of any water pipes that are available or a single 6 ft. mild-steel rod of not less than $\frac{3}{4}$ in. diameter or a pipe of 1 in. diameter. The pipe or rod should be driven as nearly vertically as possible, and the connection to the electrode should be made above the ground surface so that it may be inspected.

(iii) The neutral distributors should be connected to earth at the base of poles at four points per route-mile, in addition to the earth at the substation. Including the substation the ratio of any two of these resistances should not exceed 4, and the greatest should not exceed 10 ohms,* and should preferably be considerably less.

(iv) Water mains should not be used for earthing at the substation.

(v) An earth-continuity conductor should be used throughout each installation, and should be connected to the neutral conductor and earthing lead at the meter board.

(vi) No switch or fuse should be used in the neutral throughout the installation, but removable links may be provided for test purposes where required.

(vii) The resistance of the earth-continuity conductor from any appliance to the meter board should not exceed 0·5 ohm, and this should be verified in each installation

* In areas where the resistivity is exceptionally high it may be necessary from economic considerations to permit a higher value of resistance than 10 ohms.

by means of a current of at least 10 amperes flowing for 5 minutes, before protective multiple earthing is used.

(viii) Two separate electrodes should be provided for earthing (*a*) the high-voltage system neutral point and/or any metal-work related to the high-voltage system and electrically separate from the metal-work of the low-voltage system, e.g. the earth wire, and (*b*) the low-voltage system neutral point and the metal-work of the low-voltage system. These should be so situated that the low-voltage earth electrode is not within the resistance area of the high-voltage earth electrode. If this precaution were not taken, then a breakdown on the high-voltage system, causing current to flow through the high-voltage earth electrode, would result in the potential-rise of the high-voltage earth electrode being communicated to the neutral of the low-voltage system and all apparatus frames connected to it.

(ix) The distribution system should be so protected that in the event of contact between a phase wire and neutral at any point up to the consumer's terminals the supply would be automatically cut off from the defective section.

(8) ACKNOWLEDGMENTS

The Association acknowledges, with thanks, the co-operation throughout the multiple earthing tests of Mr. E. F. H. Gould, who conducted the investigations on interference with the Post Office telephones and supplied the information in this paper dealing with the matter, and the North-Eastern Electric Supply Co., the Wessex Electricity Supply Co., the County Borough of Hastings Electricity Department, the County Council of Dumfries, and the Borough of Cheltenham Electricity Department for the provision of test facilities. Thanks are also due to various members of the staffs of these undertakings, and to Mr. H. W. Grimmitt, of the Electricity Commission, who assisted with the tests, to Mr. G. F. Shotter for supplying data on earth-leakage circuit breakers, to Mr. E. Fawssett and Mr. J. S. Pickles for carrying out the tests on earth-leakage circuit breakers, and to the latter for allowing the E.R.A. to make use of the results.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 14TH APRIL, 1937

Mr. S. W. Melsom: It is important to point out that all the difficulties with which the paper undertakes to deal disappear if one employs a cable system instead of, as in the cases dealt with in the paper, overhead lines. The metal sheath of the cable provides all the earth connection required, and it is not necessary to worry about multiple earthing.

The author refers to earthing in consumers' premises as giving a measure of safety to the consumer. It is, however, a much-debated question whether in certain circumstances earthing does give protection, and whether there might not be a greater degree of protection without it. The question has been under discussion by the Wiring Regulations Committee of The Institution for the last 15 years. In a bedroom with a linoleum-covered floor the earthing of the case of a radiator introduces a danger where little or none would otherwise exist. If the element of the radiator happens to become connected to the case through failure of the insulation nothing happens to anyone who touches the case, because he is on an insulated floor; but if the case is earthed and someone accidentally puts one hand on the case and another into the live element, a fairly common occurrence, he will get the full voltage across him, because of the existence of the earth wire. Personally, in my own house I would not earth if I could possibly avoid it; where I had an insulated floor I should regard the all-insulated system as very much safer than bringing in an earth wire. On the other hand, there are pieces of apparatus, such as a cooker (possibly standing on a concrete or stone floor), or a flat iron, where it is probably essential to bear in mind the possibility of a breakdown of the insulation and to take some steps to reduce the potential should the insulation break down. For that purpose the earth-release trip seems to be by far the most satisfactory method. Safety is, after all, only comparative, otherwise we should reduce the voltage in all homes to 30 volts. It is difficult to understand the present attitude towards insulation; we can insulate for 100 kV nowadays, and clearly it is possible to insulate properly for 250 volts.

The principal safety requirements of any electrical apparatus nowadays are (1) that it shall stand a breakdown-voltage test, which means very little, and (2) that it shall have an earthing screw. I suggest that for the great bulk of apparatus in ordinary houses used in rooms having wooden floors we should have a very much higher degree of safety if the cost represented by the earth wire and the multiple earthing were laid out on the insulation of the apparatus. Some years ago Mr. Gilbert ran a great campaign for an all-insulated system, but in my opinion he set to work in the wrong way. He wanted first the conductor, then a piece of insulation, then a metal case, and finally some insulation on the outside of the metal case. I should prefer to put the insulation where it really belongs, namely between the current-carrying part and the exterior metal.

The author deals with the question of the rise of voltage which occurs if the neutral conductor is broken; but there is the much more important case where two conductors on a 3-wire system—and presumably the same thing would happen with a 3-phase system—become short-circuited. It is indisputable that due to this cause it is possible to have a substantial rise of voltage: the neutral may reach a potential of as much as 200 volts above earth, with the result that the cases of all the apparatus in a building may be automatically raised to that voltage. I remember measuring 460 volts across what was normally a 240-volt supply, the increased voltage being due to a short circuit on the mains in the road, and I have had instances cited to me since of several fires due to the same cause which occurred in dwellings.

Frankly, I am afraid of multiple earthing. A properly insulated earth wire can be disconnected from earth and the condition of the installation ascertained by ordinary testing, but I gather that with the multiple earthing

system quite a large leakage current may be flowing permanently which cannot be detected, except, perhaps, by an ammeter in the circuit. A fairly large current flowing to earth means a fairly high potential, and I am afraid of dangerously high voltages occurring unexpectedly in places where they should not occur. The risk of fire is not dealt with in the paper, but it is possible to strike and maintain a most dangerous arc with a voltage of about 15 volts. It may be said that with modern insulation it is impossible to have large leakage currents; to which, of course, the answer is that with modern insulation we do not want quite so much precaution. One great weakness of the multiple earthing system is the liability of the connections and contacts to corrode unless there is frequent supervision. Bearing in mind all of the factors involved, such as degree of safety over a long period of years and relative cost, it appears to me that the best method for installations in small dwellings in rural areas is to run an all-insulated system for the lighting and an earth-leakage circuit breaker for protection of such apparatus as cookers. And, although I am a member of the E.R.A. Committee responsible for the proposals contained in the present paper, I would personally debar multiple earthing of consumers' premises on the grounds that it is more costly and much less safe than other methods.

Mr. P. B. Frost: This investigation began with an attempt to study the possibilities of protective multiple earthing, and it developed into a comparison between the degrees of safety obtainable by protective multiple earthing, ordinary methods of earthing, and earth-leakage protection. I have been in fairly close touch with the committee which has controlled the experiments on which this paper is based, and I am in general agreement with the conclusions reached. I shall therefore only have to criticize the practical applications of protective multiple earthing.

The tests were made in a number of very small villages, where the Post Office has no cause for fearing that difficulties will arise from interference or from false signalling on bells. But if protective multiple earthing is applied to much larger systems, with long distributors run along sparsely-populated narrow roads, we should not assume without consideration that there will be no trouble from noise interference. In such cases the parallels between open telephone wires and power distributors will be long, and road separation will be small, and therefore the matter will still require to be watched. I hope, therefore, that protective multiple earthing will not be applied to large systems. Protective multiple earthing, with its relatively large leakage currents in the earth, will, I am sure, be a definite and serious limitation upon the extent to which "joint construction," or the running of telephone wires and power wires on the same poles, can be adopted. I must assume that where distribution engineers voluntarily adopt a system of protective multiple earthing with the full knowledge that there will be no means of measuring or recording earth-leakage current, they will look to the Post Office to call attention to any heavy leakage currents which occur.

With regard to the application of the recommendations recorded in the paper, there is a very important point which I have to raise. Certain recommendations are made concerning the disposition and the values of the various earth-connections to the neutral, the object being to ensure that the earth-potential point or neutral point of the neutral conductor shall lie at about its mid-point. Under these conditions it is possible to allow for a 60-volt drop from end to end under the worst anticipated fault conditions, and still not exceed a potential difference of 30 volts, the maximum safe value, between any of the connected apparatus frames and earth. It is not easy to see how the required conditions can be attained in the case of a distribution system which includes a certain amount of underground cable. If these cable sheaths are bonded to the neutral, no earth connections made at other points will offset the low resistance to earth of the cable sheaths, and therefore the system will be in a sense top-heavy, in that the low-resistance earths are all connected near one end of the neutral conductor.

With regard to common earths, the author very properly points out that it is necessary to avoid using a common earth for the high-voltage side of the transformer and the low-voltage network—for example, at the substation. As is pointed out at the end of the paper, if an earth fault occurs on the high-voltage side the potential to which that neutral point is raised will be communicated to the earth around the substation and, in the absence of precautions, also to the low-voltage neutral, and to everything connected to it. The two earth systems must therefore be well separated, and, if any length of underground cable is used on the low- or the high-voltage side, or both, it will be very difficult to keep the two earth systems separate and sufficiently far apart to avoid a voltage on one being communicated to the other.

I feel very doubtful whether distribution authorities will follow the author's necessarily exacting recommendations sufficiently faithfully to provide adequate precautions against an abuse of protective multiple earthing, either at the outset or after a major mains extension; and for that reason I prefer the earth-leakage protective system.

Mr. T. C. Gilbert: The formula for tripping current given on page 765 is only approximately correct, and this provided that the resistances R_f and R_e are very high. A much more exact form would be

$$i = 2\,400a/\sqrt{[X_c^2 + (R_f + R_e + R_c)^2]}$$

where R_c is the resistance and X_c the reactance of the trip coil.

An error has crept in at the top of the right-hand column of this page, where the figure 3 200 ohms should be 3 400 ohms.* Thus we have

$$\frac{2\,400 \times 50}{3\,400 + 600} = 30 \text{ mA}$$

In the same column the author states that under certain conditions the leakage switch will not operate if the resistance of the fault and earth electrode combined is more than 1 000 ohms, and that a voltage of 72 volts will be impressed upon the metal-work. This is not the case, as will be seen from the simple example illustrated

* Corrected for the *Journal*.

in Fig. A. If $R_f = 600$ ohms, $R_c = 200$ ohms, $X_c = 0$, and $R_e = 400$ ohms, then

$$i = \frac{72}{600 + 200 + 400} = 60 \text{ mA}$$

and the voltage to earth is given by

$$U_e = \frac{60}{1\,000}(200 + 400) = 36 \text{ volts}$$

and not 72 volts as stated in the paper.

I consider this an extremely serious error, as any uninformed person reading the paper and knowing that combined earth and fault resistances of 1 000 ohms are often met with in practice will come to the conclusion that the leakage switch cannot assist him to keep leakage potentials to a safe low value. A careful examination of the facts would have shown that only by means of the leakage switch can isolation of the circuit be ensured under the circumstances visualized in the paper.

Fig. 4 purports to show conditions of operation of leakage switches on 240-volt supplies; conclusions drawn from this figure must be misleading, for the following

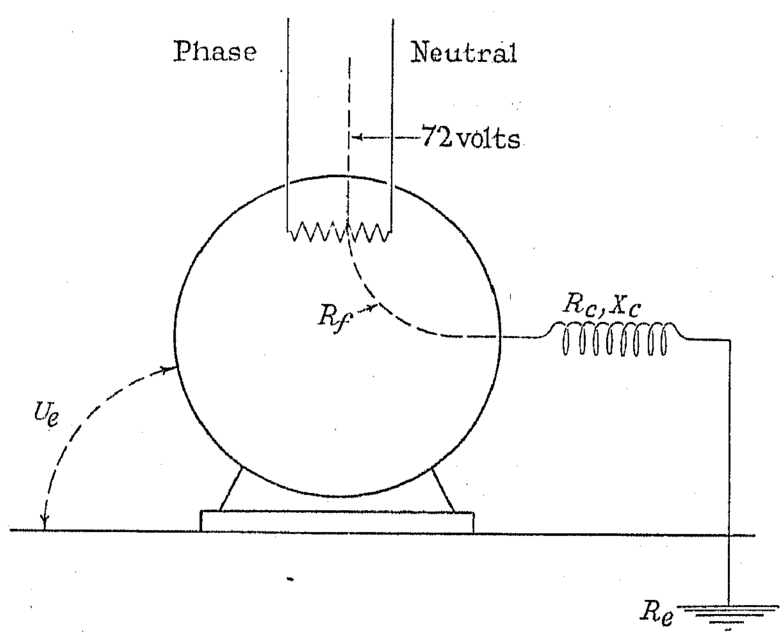


Fig. A

reasons: (1) The reactance of the trip coil is neglected. (2) The ordinate gives the potential at the fault point, but the horizontal line " 30 volts " represents the permissible potential upon metal frameworks. In the ordinates, therefore, the fault resistance is included, but in the horizontal line it is excluded. (3) The transverse lines have no reference to leakage switches likely to be used in good practice. For instance, 200 ohms and 15 mA infers a switch with a tripping voltage of only 3 volts, whilst coil resistances of 1 000 ohms are unknown. Such fine windings could not stand up to ordinary use, especially where risk of excess voltages exists. (4) We are not concerned in practice with combined fault and earth resistances of 16 000 ohms, as those lying between 100 and 5 000 ohms are more common. Fig. 4 should therefore concentrate upon the lower values.

In order to design Fig. 4 correctly, tripping currents should be ignored, and only the tripping voltage considered. Taking the voltage across the coil as U, earth resistance excluded, the voltage to earth upon metal frameworks operating the switch will be given by

$$U_e = U\sqrt{[X_c^2 + (R_c + R_e)^2]/X_c^2 + R_c^2}$$

In contrast to Fig. 4, fault resistance does not appear in this formula, as it is of no influence. If, for example, $R_c = X_c = 200$ ohms, and $U = 15$ volts, then a characteristic of the switch can be obtained similar to curve (1) of Fig. B. From this it will be seen that the switch functions at 30 volts with 330 ohms earth resistance, and such resistances are not difficult to obtain in practice. Even in sandy soil, with specific resistance of

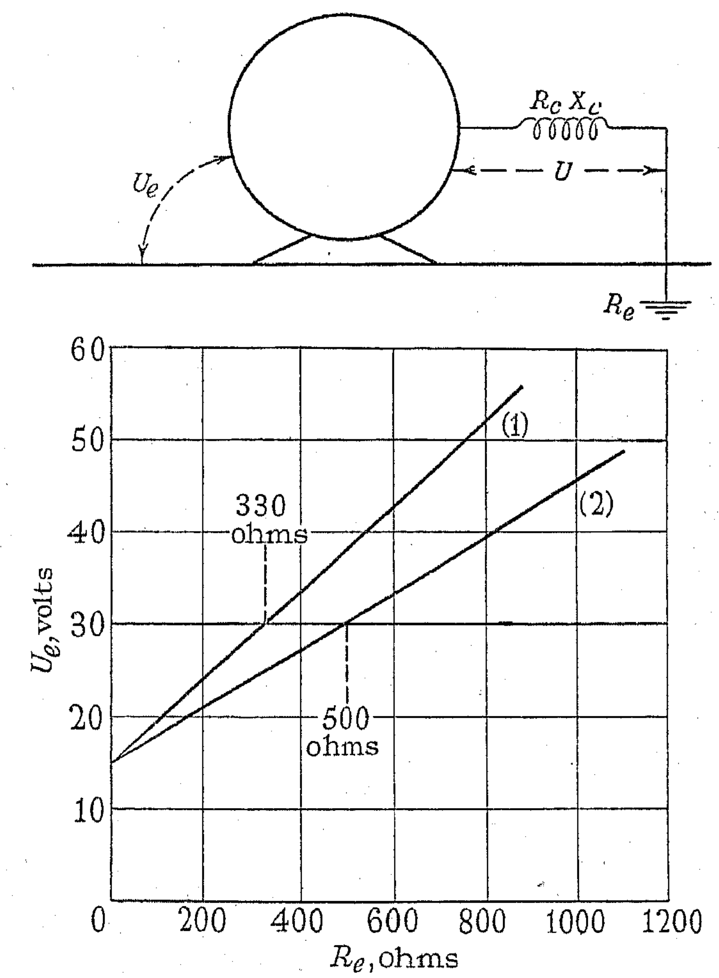


Fig. B

Curve (1): $R_c = 200$ ohms, $X_c = 200$ ohms, $U = 15$ volts.
Curve (2): $R_c = 300$ ohms, $X_c = 300$ ohms, $U = 15$ volts.

70 000 ohm.cm., a 6-ft. pipe would have a resistance of 340 ohms. To consider another switch, with $R_c = X_c = 300$ ohms, and $U = 15$ volts, operation will take place at 30 volts with 500 ohms earth resistance, shown in curve (2) of the graph.

From this it will be seen that the higher the trip-coil resistance and reactance, the less the dependence upon the earth electrode resistance; but practical considerations of strength and permanence restrict such resistances, etc., to about the figures stated above. Fig. 4 gives none of this essential information.

I cannot follow why such importance is assigned to fault resistance, R_f, in connection with leakage switches, where it is without influence, in view of its complete neglect in the paper in connection with earthing and protective multiple earthing, where it is of the highest importance. Fault resistance is only mentioned once in a very general way, whereas if a true comparison of the three protective

systems were made it would appear in Figs. 1 and 2, in addition to its sole appearance in Fig. 4; it would also appear in "Recommendations" (iii) and (iv) (page 778), and in "Proposed Conditions" (vii) and (ix) (page 779). Instead, fault resistance is only considered in connection with the leakage switch, which thus receives unfair treatment, and the figures and conclusions are thereby rendered valueless from a practical point of view. It surely cannot be visualized that all earth faults are "dead to earth" in all cases with earthing and protective multiple earthing, and are only complicated by fault resistance in connection with leakage switches.

I think it is well known that the Electricity Supply Board of the Irish Free State, mentioned in the paper as enjoying the benefits of protective multiple earthing, utilizes the leakage switch because of the incidence of fault resistance in cooker protection in rural areas. The only satisfactory way of calculating permissible earth-to-neutral resistance is by means of the formula

$$R_e = \frac{\text{Permissible potential}}{\text{Fusing current}}$$

where (see page 778) the suggested permissible potentials are 30 and 15 volts respectively [paragraph (iii)], and the current is such that the fuse will be blown in a safe short period (i.e. is $2\frac{1}{2}$ times the fuse-link rating). In using this formula the efficiency of protection, as also in the case of the leakage switch, is rendered independent of (*a*) the earth/neutral resistance, (*b*) the reactance of the circuit, and (*c*) the fault resistance R_f; that is, independent of the total impedance of the fault-current circuit. Had this method been used throughout the paper a much truer comparison of the three protective systems would have been possible.

On page 776, five alleged disadvantages of the leakage switch are set out, which, however, will not bear examination. No. (i) can be alleged against all protective devices, especially fuses, and is not peculiar to leakage switches. No. (ii) ignores the fact that there is no comparable ease of test with either earthing or protective multiple earthing, and it is difficult to understand why a particular attribute of the leakage switch should be included in any list of disadvantages.

No. (iii) is again no disadvantage of the switch, as such, but only of a doubtful method of construction. As regards No. (iv), does the author acquiesce in leakages of from 30 to 50 mA from cooker hot-plates? Would he tolerate such leakages from any other device, or from wiring, without expecting protective devices to operate? Such leakages are dangerous to life, and should be isolated. Apart from the requirement contained in the I.E.E. Wiring Regulations that leakage switches should operate with a current of not more than 30 mA, these devices can easily be set up to overcome this difficulty. In any case, the author overlooks the fact that the leakages complained of increase with temperature, and are greatest if the plates are over-run (excess voltage) or are heated without utensils being placed upon them. Regarding disadvantage No. (v), I would point out that as soon as the operating voltage is reached the leakage switch will function, irrespective of the resistance of the human body compared with the earth resistance.

Table 1 gives the operating voltages of leakage switches at present in service, and thus judges them by a standard that has not yet been established in this country. When these switches were installed and tested the only relevant requirement to be found in the I.E.E. Wiring Regulations was that they should operate with a current not exceeding 30 mA; no operating potential was stated or implied. It is reasonable to assume, therefore, that manufacturers and installers were not concerned with the limitation of leakage potentials, and that the switches were constructed with high-impedance coils in order to give reasonable certainty of operation. The author's general statement that the switches referred to in Table 1 are of an early type, is inadequate.

Still dealing with leakage switches only, I cannot follow Recommendation (v) on page 778, as surely this condition must be met whatever the protective system selected. I would, however, entirely concur with (vi), as most of the author's experiments can only have been carried out with unusual equipment. He might give a lead here regarding the permissible impedance limits of trip coils, in view of the fact that potential limitation is the object in view and not operation with specific leakage currents.

Turning to other aspects of the paper, I agree that in connection with protective multiple earthing the breakage of the neutral by itself is unlikely. The important factor to take into account is neutral discontinuity, a very different matter, and this may occur, completely or partially, at any terminal or junction. More connections are made to a neutral line than to any other, and every one is a potential source of danger, whilst the possible breakdown of a static balancer must not be left out of account. In view of the dangerous possibilities of complete or partial neutral disconnection on a distributor or service, and bearing in mind Continental experience, I feel that this matter has been dismissed altogether too lightly in the paper. The very optimistic view expressed in Condition (ix), page 779, can hardly be met in practice without consideration of line impedance and fault resistance, both of which are ignored, whilst Continental experience again shows that the average operating time is $\frac{3}{4}$ minute,* which is too long to ensure safety with any form of protective multiple earthing.

The footnote on page 778 indicates that financial considerations may form grounds for ignoring the stringent recommendations of the paper, and a state of considerable danger be allowed to exist.

The paper fails to take into account the dangerous conditions that may be set up with protective multiple earthing in the event of an earth fault on a phase line, a broken phase line in contact with earth, or a phase fault in the installation. Continental experience shows that the latter occurrence is a prolific cause of fires in rural installations, apart from the danger likely to arise by reason of high neutral potential, whilst a phase line in contact with earth cannot be isolated by ordinary means. Evidence as to the effect of these adverse factors may cause the author's recommendations as to the adoption of protective multiple earthing to be reversed.

In those countries that have utilized protective multiple earthing it is considered that trouble due to the cell effe

* O. Löbl: "Earthing: Neutral, and Protective Systems" (Julius Springer, Berlin, 1933), p. 26.

of electrodes in parallel is intensified in connection with multiple electrodes, the result being the gradual disappearance of certain electrodes. Electrolysis from similar causes appears to have been the reason for the abandonment of protective multiple earthing in Australia recently, and was one of the reasons for the similar step in some districts in Germany. It appears that serious attention should be given to this aspect of the proposal.

I consider that the instances chosen in the paper for practical tests of protective multiple earthing are not typical, as these consist of purely overhead systems. In a great many cases, and in my view the majority of cases, such rural lines are extended from small underground systems, preventing the application of the conditions stated in the paper, which therefore become inconclusive for most reticulated areas. Protective multiple earthing cannot possibly be recommended for such areas.

Had the three protective systems been compared on a basis of equality as regards fault resistance, it would have been clearly established that with earthing and protective multiple earthing the variable resistance factor of the fault or earth-neutral connection must always prevent the complete and effective control of leakage potentials so necessary in the interests of safety to human beings and animals, and that neither system can afford any real solution to the rural problem. In only one way, namely by installing circuit breakers responsive to some predetermined potential—the paper visualizes 30 volts—both at consumers' premises and at the rural substation, can the desired limitation of potential and certain isolation of faulty circuits be ensured. Any proposal to adopt a protective system below this level of efficiency represents a retrograde step, and one that the electrical industry in this country should not be encouraged to consider in view of its gradual or complete abandonment elsewhere.

Mr. W. Fennell: I am very interested in this subject because in the Mid-Cheshire area we have some districts where earthing is difficult. There are places where we cannot get an earth resistance of less than 1 000 ohms on a rod about 10 ft. in length driven into the subsoil (dry sand). Where the turf has rotted year after year there is a thin carbon skin covering the surface of the ground. I have seen earth wires sparking to the turf where they pass through to the earth plate buried below.

The problems referred to in the paper are confined to bad earthing districts and will therefore rarely arise in towns, where there are plenty of water pipes and gas pipes. If the dangers that one visualizes in reading a paper like this were common, we should not have had in the whole of the United Kingdom last year only three or four human fatalities due to touching earthed casings in and around domestic premises. On industrial premises good earth-connections can be obtained to water pipes, etc., and there are regulations governing such premises which the Home Office is in a position to enforce. Premises in rural areas are almost the only places where any serious difficulty arises. On the premises of private consumers there is in practice no means of enforcing either that the ordinary earthing system shall be well maintained or that earth-leakage circuit breakers shall be installed on apparatus, or, if they are, that they shall be kept in order. There is, however, an automatic protection for the consumer in that wherever there is a bad earthing district it is just as difficult for the consumer to get a good earth connection to pass the fatal current of 25 mA through him as it is for us to get a low-resistance earthing connection on his apparatus; and this, I presume, is the reason why we have hitherto escaped so lightly.

It seems to me that there is the choice in practice either of having single-point earthing, as at present, or of adopting multiple earthing in bad cases; because I cannot believe that consumers will be persuaded to buy earth-leakage apparatus in the large quantities which would be required, and, having bought it, to keep it in order for more than a year or two. Table 1 shows that after 2 years there were four "potential deaths" on those circuits where earth-leakage circuit breakers had been in use. What sort of conditions can we expect when they have been in use for 5, 7, or 10 years without any maintenance, in all kinds of difficult locations, and especially in farms and stables? It seems to me, therefore, quite impossible to look to the earth-leakage circuit breaker as a permanent solution, both on the score of expense and on that of maintenance. We have consequently to decide whether to go on as we are or to adopt multiple earthing; and I suggest that it is only necessary to prove that multiple earthing is safer than single-point earthing to settle the question. The author finds that multiple earthing is 8 or 9 times as good as single-point earthing. This being so, it seems to me that the only thing against it is the possibility that the Post Office circuits may be affected if there are very long low-voltage distributors. In Table 2 the author refers to cases in Northumberland, Berkshire, and Sussex where there are low-voltage distributors having lengths of 1 050, 1 557, and 2 084 yards respectively. I suggest that that is not electricity supply but merely electric lighting supply; in a proper supply system such long distributors cannot be tolerated. Therefore, as it is only to very long circuits that the Post Office take exception, we can regard the case as proved for multiple earthing in rural areas where a proper system of supply is provided for the consumers.

Mr. R. J. J. Swan: In the part of Buckinghamshire in which I am operating we are fortunate in being able to get a very good neutral earth-connection. In the early days of supplying cookers we made a test of the earth connections of the consumers and obtained values of 9–10 ohms; it was therefore clear that the cooker fuse would not blow in the event of an earth. On investigating we found that the greater part of that resistance was in our own earth-plate at the transformer. An 18-in. square galvanized-iron earth plate was then installed, and on making further tests we found that the earth resistance varied from 5 to 35 ohms, 35 ohms being the highest out of some 120 or 130 tests taken. It was found, however, that by burying about 90 yards of 0·1-sq. in. copper wire in a circle 9 ft. in diameter we could obtain an earth-plate resistance of from 2 to 4 ohms.

Assuming we are now to be allowed multiple protective earthing with the condition that we must earth the neutral at four points to the mile, on our system we can get four points at about 3 ohms each and thus have a very satisfactory neutral earth resistance. If we are allowed to connect to the neutral all frameworks of apparatus on hire—i.e. apparatus which is a potential danger at times

—in every case if it breaks down the fuse will blow, because it has such a very low resistance. I do not think that in any circumstances will there be a rise in voltage above the 30 volts which is considered safe. So far, therefore, as rural areas are concerned where a very low earth resistance can be obtained for the neutral, I think that protective multiple earthing is going to be a very great help. I have rather a doubt as to the advantages of driving a $\frac{3}{4}$-in. pipe 6 ft. in the ground for each consumer.

Mr. C. A. Cameron Brown: I would remind Mr. Fennell that as far as farms are concerned two-thirds of the voltages quoted in Table 1 would be dangerous. The fact that there have been only three human fatalities in a year is no cause for congratulation when danger to farm stock is a serious item. Another reason why we should not be quite so satisfied about the freedom from fatality is that more than half the farms now electrified have been wired during the last 5 years: in 10 or 15 years' time the wiring will not be quite so good. In view of the appalling state of the wiring of some farm premises it is surprising that there has not been a serious accident at least once a month!

In support of the author's evidence as to the gravity of the situation where water mains are absent, I would mention that out of 168 tests on actual farm earths taken at random within 50 miles of Oxford, 67 failed to blow a 5-ampere fuse, 83 a 10-ampere fuse, and 100 a 20-ampere fuse. These figures assume that there was no resistance in the circuit other than the earth resistance; the situation would have been much worse otherwise.

With regard to protective multiple earthing, there are two doubts which deter me from supporting this system. In the first place, I feel that a metal-sheathed wiring system is quite out of place on a farm, unless it is of a standard that the average farmer cannot afford. The alternative tough-rubber-sheathed installation means continuous bonded wire with protective multiple earthing, and this is a disadvantage, particularly for isolated pieces of apparatus, where the obvious thing is the single local earth. Secondly, with a protective multiple earthing system with several installations on an l.v. line, an earth fault in one installation may fail to blow the fuse. Does this mean that the resulting potential is communicated to all the other consumers on the system? If so, this introduces a grave risk, because over-fusing—the insertion of nails, and so on—is by no means uncommon. In addition, I believe that the total impedance in the circuit of some l.v. distributors may be as high as 10 ohms, and if it is anything approaching that figure the situation will be much the same.

I should not like it to be taken that the tests on trips recorded in Table 1 are normal ones. Many of these trips must be very old-fashioned, and I think that tripping at 200 volts can be overcome by good and properly-made apparatus. The earth-leakage trip is not such a complicated piece of apparatus that it cannot be made to a proper specification and kept to it, in spite of Mr. Fennell's criticism as to its life.

I do not think that there is sufficient evidence in the paper to justify going ahead immediately with protective multiple earthing. It seems to me desirable, however, that some supply authority should be authorized to run a protective-multiple-earthing system on a large scale for, say, an observation period of 5 years. The faults which pessimists expect on protective-multiple-earthing systems are not likely to develop within 6 months.

Mr. H. W. Grimmitt: I do not think that the question of accidents can be dismissed so lightly as Mr. Fennell would like to dismiss it. The reason why there have not been accidents in the past is, of course, that if one cannot blow fuses usually one cannot kill people either; but the majority of accidents are freak accidents, and, with the growing amount of apparatus in use and the deterioration of wiring, accidents will become more general if nothing is done.

Most of the speakers do not seem to realize the nature of the networks which will be protected either by earth-leakage trips or by protective multiple earthing. They will not be extensive systems, because with large systems there are bound to be water supplies and good earths, and the ordinary earthing conditions which have prevailed for the last 50 years will continue. The villages without a water supply in this country usually have populations of less than 200, and therefore I cannot visualize many miles of l.v. line being protective-multiple-earthed. Again, it is bad practice to have long overhead l.v. lines. Much of the criticism is due to the author's statement concerning four earth-plates per mile of line, which conjures up a vision of many miles of line, whereas usually it will only be a case of protecting a line for $\frac{1}{2}$–$\frac{3}{4}$ mile from the substation.

Where the system is a mixture of cable and overhead line and there is a good earth at the substation, I suggest that by far the best method is to run an additional earth wire from the good earth-connection along the overhead line and to connect all extraneous metal-work to this earth wire, rather than have a mixed system of protective multiple earthing and ordinary earthing. This arrangement has proved very satisfactory in Cumberland, where owing to the ground being chiefly rock it is sometimes difficult to get good earth-connections. In considering whether to use earth-leakage trips or an additional wire or multiple earthing the question of cost must be seriously investigated, but in this respect I do not think there is much to choose between the three systems. Earth-leakage trips may prove the cheapest.

Another interesting point raised in the paper is the best position for earthing the neutral in the case of ordinary earthing. In small villages—and it is only small villages which are considered in this paper—it is customary to endeavour to earth the low-voltage neutral at the substation, which is invariably in the corner of a field and in a position where cows collect. The cows are generally killed not by coming into contact with metal-work but by a voltage gradient over the earth electrode. One can usually find a much lower earth resistance in the village than at the substation, and it is at this point that the neutral should be earthed.

Dr. W. G. Radley: There is only one type of telephone system in use at present by the Post Office which is likely to be seriously affected by the proposed system of multiple earthing. It is one in which an earth is used at each telephone subscriber's premises for signalling purposes. Unfortunately, that system is designed especially for long extension lines, and so is chiefly found in rural areas, where protective multiple earthing is most likely

to be used. The possibility feared is that large unbalanced load currents in the power network may transfer to the telephone system, during normal service, voltages high enough to cause continuous bell tinkling. The voltage may be picked up by induction in the case of a long parallel, where, for example, both sets of lines run along the same road, or it may arise from the close proximity of the two sets of earth connections.

Theoretical considerations and practical experience lead us to the conclusion that the chief source of interference is the proximity of the two sets of earth connections. At the one end, the telephone exchange is not likely to be very close to the substation, and therefore the only connections which have to be considered are those on the power consumer's, or telephone subscriber's, premises. Investigations by the E.R.A. have shown, however, that at a distance of 10 yards from a 4 ft. long by $1\frac{3}{8}$ in. diameter pipe electrode the potential is only about 2 or 3 per cent of the total potential-difference between the electrode and the true earth.

A rather different problem arises if the power supply system is connected to a local water system such as a pipe running round the house or garden. There was one case in the tests described in the paper where the neutral of the power system was connected to a water pipe which ran down a drive into a field. A test earth electrode about 9 yards from the pipe picked up 70 per cent of the total voltage-drop to earth. It is such points as these that require careful watching, but if they are watched and if commonsense precautions are taken with regard to the total voltage-drop we have no need to fear interference effects.

In conclusion, I should like to ask the author one question. By providing a neutral conductor for earthing the consumer's apparatus on the consumer's premises, are not the supply authority assuming a responsibility, and perhaps a legal liability, gratuitously?

Mr. W. W. Wood: When a leak occurs to earthed apparatus and the fuses do not blow, the whole of the supply voltage maintained at the terminals has to be absorbed at two points: (1) the earth electrode of the consumer; and (2) the earth electrode of the substation, or any other return electrodes. If the consumer's earth electrode is of equal resistance to that of the substation, then half the line voltage is available to give a shock either at the consumer's house or at the substation. It does not matter whether the resistance is high or low; the shock voltage at each place simply depends on the ratio of the two resistances. From this point of view, therefore, the higher the resistance at the substation compared with that at the consumer's premises, the better it is for the consumer. Where a number of consumers are concerned, the situation is a little more complicated, but it can still be said that the amount of shock which one consumer will get is the ratio of his earth resistance to that of all the other return paths in operation at the moment.

The only way in which earthing can give protection against shock is by causing an interruption of the supply —one cannot stress this point too strongly.

Now with protective multiple earthing a fault causes a short-circuit since the earthed metal is also connected to the neutral conductor, and under ordinary conditions is much more likely to cause such interruption of the supply. The author, however, thinks it necessary to consider cases where the neutral conductor itself may be broken, and then the same principle applies to the protective-multiple-earthed system as to ordinary earthing, with the added disadvantage that when a sustained voltage causes a consumer's section of the neutral wire to be above earth potential, all earthed metal on his premises is also maintained at such a voltage above earth.

The reason why earth-leakage trips are a great deal better than multiple earthing is that they interrupt the supply as soon as a dangerous potential exists on the consumer's apparatus.

There is a very simple way of determining at what shock voltage the earth-leakage apparatus will operate. According to the I.E.E. Wiring Regulations, the leakage trip must operate with not more than 30 mA; now the voltage necessary to force a current of 30 mA through the trip coil varies in different designs of leakage trips from 30 down to about 15 volts. To that voltage we have to add the potential drop caused by the flow of, say, 30 mA in the earth resistance; thus if the earth resistance is 10 ohms this potential drop is 0·3 volt, so that the total shock voltage (assuming the maximum of 30 volts for the trip) will be 30·3 volts, and in such a case this shock voltage cannot be permanently exceeded.

There is another point which I should like to raise regarding multiple earthing. In Fig. 7 the author shows the earth-continuity conductor connected to earth and directly to the neutral on the live side of the main switch, and in another part of the paper he recommends that a switch should not be included in the neutral circuit. The neutral conductor is connected to every piece of metal in the consumer's house, and if a serious fault occurs in another part of the system the consumer may get a shock from everything he touches, and open sparking may take place, even although there is no fault on his own installation, and when he opens his switch it makes no difference. I maintain that the neutral connection should be made to the dead side (of the main switch), so that the consumer can disconnect himself completely from the supply.

Mr. F. C. Raphael: The author is wrong in thinking that the leakage circuit-breaker is a German invention; it was brought forward by a young English electrical engineer in 1896 but was not taken up.

A great part of the paper is based on the assumption that if there is any leakage the potential of the frame must not exceed 30 volts, but we have never had it explained why alternating current is dangerous above 30 volts. In ordinary medical applications of alternating current the doctors go up to 100 mA in exceptional cases, and I think it is safe to say that it would be extremely difficult to kill a man by a current of less than 150 mA. If, however, we take 150 mA as the possible fatal current, and 30 volts as the maximum voltage, we find that with a skin resistance of anything higher than 200 ohms the current of 150 mA will not pass. The skin resistance, however, is, I believe, more like 400 ohms, making 800 ohms for the two skin contacts; and 100 volts applied to this resistance would only give 125 mA. Consequently we should have about the same degree of safety as is given by an earth-leakage breaker if we put in a double-wound transformer and earthed the middle point

of the secondary. If it were a 1:1 transformer we should never have a higher voltage than 100 volts to earth. If, however, we wanted to be safer still, we could transform down to 100 volts with the transformer and limit the voltage to earth to 50 volts by earthing the centre point of the secondary.

There is another point to be considered. These breakers are designed to break at 30 mA, but they will certainly not break at this current if they are short-circuited by the earthing wire, as laid down by the I.E.E. Wiring Regulations. It is, however, desirable, if we can, to make installations safe by standard methods rather than to use special automatic devices or to transform down to a non-standard voltage. These highly-insulated villages want the earth—literally and not metaphorically—and it should be the duty of the supply authority and not the consumer to supply it if their voltage would be dangerous on standard methods of wiring which presume the existence of facilities for earthing. I feel sure that the multiple-earthed neutral is the correct solution, but it must be applied in the correct way.

The author seems a little uncertain about the question of solid links instead of fuses. In the body of the paper he says (wrongly) "From this diagram it will be clear that the elimination of neutral fuses in the installation is not essential, but on the other hand they serve no useful purpose, and discontinuance of their use would effect a saving in cost." In his "Conclusions," on the other hand, he recommends, rightly, that no fuse should be used in the neutral. It is in fact very dangerous to have fuses in the neutral, because, if a fault occurred in the neutral of the consumer's wiring, part of the installation would be fed through the fault if any neutral fuse were blown or withdrawn.

Dr. S. Whitehead: In order to suppress disturbance from domestic appliances to the level at which we now aim, paying due regard to the economic aspect, it is very desirable, and may be essential, to employ a choke in the earthing lead in a number of instances. For such a choke to be of reasonable cost and dimensions, a certain amount of resistance must be allowed. To avoid dangerous voltages, however, the conditions of which the author lays down, it is clear that the resistance of the earth electrode and associated conductors must in ordinary earthing be sufficiently low, so as to allow a margin of safety, permitting the addition of the resistance of the choke. For the majority of consumers such a margin may be said to exist; but we are dealing with standard products and have to envisage the unfavourable cases. The author has shown that the worst cases are so bad that, in point of fact, we should want a negative resistance; nevertheless, his proposals afford the possibility of a solution.

If, when the earthing resistance of an installation exceeds a certain value, protective multiple earthing or earth-leakage circuit breakers are employed, then this maximum earthing resistance may be taken for specification purposes as the worst case. Again, if the fuses present in the circuit are of suitable rating, the maximum safe resistance to earth, based on the maximum permissible voltage-rise (e.g. 30 or preferably, for this purpose, 50 volts), can exceed this standard earthing resistance, if the latter is reasonably low, by an amount greater than the resistance of the choke. It will then be safe to use the choke, if suitable fuses are provided. Where protective multiple earthing is used a choke in the earthing lead is rarely necessary. Such a choke is also unnecessary with earth-leakage circuit breakers when an ordinary earthing lead and electrode is not connected in parallel. If the parallel connection is used the choke can be inserted therein without danger.

The problem of earthing has, therefore, a vital bearing on the problem of radio-interference suppression, and this aspect deserves the greatest consideration. It is not a very long time since the number of fractional-horse-power motors incorporated or sold was quite small, but in 1934 about 600 000* were sold or incorporated, and the present figure is probably very much higher. Although it appears hitherto not to have been taken into serious account, this matter is of great importance because it affects the public on the one hand in regard to the cost and convenience of very widespread appliances and on the other in regard to interference with the use and enjoyment of important public services.

Mr. S. R. Siviour: I consider the earth-leakage circuit breaker may be the solution for the major problems dealt with in the paper, but I have one or two objections to some of those which I have seen and tested. Their first cost is high, they are of very delicate construction, and they will require maintenance. This will involve a great increase in the responsibilities of the undertaker, which at present merely mean putting in a service, a cut-out, and a meter requiring little subsequent attention. The supply authority does not want to have to test the consumer's circuit breaker, say, every month. The evidence of experience with earth-leakage circuit breakers given in the paper is not sufficient to judge by.

As regards multiple earthing of the neutral, much has been made of the broken neutral; but in my experience of about 300 l.v. networks, over half of which are overhead, a broken conductor is almost unknown. I should have liked to learn a little more of the experiment carried out in Australia with the multiple-earthing system.

With regard to hired apparatus, I suggest that the hiring agreement should provide for the responsibility for maintenance to be on the consumer: the Commissioner's Regulations appear to permit this arrangement.

Mr. S. C. Bartholomew: The paper refers only to alternating-current systems, but there have been cases where multiple earthing has been used with direct current. In these instances the lead sheathing of the Post Office cables was eaten away by the stray currents; in fact, in one instance unauthorized multiple earthing came to light owing to this electrolytic damage. Although there are not now many direct-current systems in this country it should be made clear that direct current is excluded from this method of protection.

Multiple earthing has been in use on a.c. systems in isolated cases for very many years. I remember it about the year 1911 at Leatherhead, and later at Egham and other places, where, subject to certain conditions, it was in use with the approval of the Board of Trade in the first instance, and then the Electricity Commissioners and the Post Office. In these cases the consumer's wiring consisted of a single-core cable with an outer metallic

* Import Duties Act Inquiry.

sheathing which was used as a conductor, being specially earthed locally and also connected to the armouring of the main cable sheathing.

(*Communicated*) As regards interference, there will always be the special case where multiple earthing may interfere with communication or signalling circuits. A case in point occurred a few years ago at St. Bartholomew's Hospital when the investigations into heart troubles in one of the blocks of wards were completely stopped by inductive effects on the circuit between the block and the central point where the heart beats were recorded by means of an Einthoven galvanometer. A frequency of 50 cycles per sec. was superposed on the record from this particular block, and as direct current only is used in the Hospital it necessarily came from outside. The originating disturbance was eventually traced to a second earth which had been placed on the public supply in the neighbourhood outside the Hospital curtilage.

The possibility of interference with broadcast reception is likely to be increased by the general extension of multiple earthing.

Mr. A. E. Morgan: After carrying out some 200 tests on earth plates in a rural area of approximately 4 000 square miles, I am in agreement with the author that in some 60 % of installations the earth-plate resistance is so high as to preclude the blowing of a 5-ampere fuse under fault conditions. This shows the unsatisfactory state of ordinary earthing as it exists in rural areas to-day.

Regarding the various means of improving the earth-plate resistance, as a result of practical tests it is found that pipes are more effective than earth plates and that a length of copper strip buried horizontally in the ground is better than pipes. In the case of one undertaking the practice has been adopted of laying a length of copper strip in the trench in which the outgoing cable from the substation is laid, and this results in a definite improvement in the value of the earth resistance.

Earth-leakage circuit breakers are subject to certain disadvantages which are not dealt with in the paper: First, owing to the very light construction of the switch heavy vibration is sufficient to cause a trip, and malicious interruptions to the supply have occurred by this means. Secondly, the trip coil usually consist of a large number of turns of very fine wire, and it is found that frequent burning-out of these coils occurs in areas where lightning disturbances are prevalent. Manufacturers might make a note of this with a view to introducing some form of spark-gap or other protection to prevent the annoyance and inconvenience which results from this type of fault. Thirdly, on page 766 the author states that "If a metal case and test key are used with the leakage circuit-breaker no protection is afforded against an insulation failure on the breaker itself." As far as I am aware there is not a single earth-leakage circuit breaker on the market to-day which has an all-insulated case. This is a very important point which should commend itself to the manufacturers.

During the discussion Mr. Gilbert has drawn an analogy between fuses and earth-leakage circuit breakers; surely this does not apply, as although it is possible to adopt some form of discrimination between fuses at the main substation and the individual consumer's premises this cannot be done in the case of earth-leakage circuit breakers. Where the latter are employed at the substation it frequently happens that the whole of the supply to the particular l.v. system is disconnected in the event of a single earth fault. This is a very serious disadvantage and cannot be tolerated under actual service conditions.

Mr. Wilfred Hill: The author and all the previous speakers appear to have concentrated on the safety of the consumer, but I should like to point out that we have also to consider the protection of our own mains. If it is difficult to obtain an earth for each consumer it is also difficult to obtain an earth for the neutral point. I have had no troubles with earth-leakage circuit breakers, and my experience is that they are cheaper to install than are reasonably satisfactory earth plates. The earth-leakage circuit breaker can be put in by a meter fixer, but the earth plate, to be any good, requires the pick-and-shovel method, and for odd additional services in a scattered area proves quite expensive.

The company with which I am connected are trying out another scheme. This covers the question of the protection of the mains, would act as an excellent back-up protection in the event of any failures such as those referred to by the author, and obviates the necessity for a first-class earth at the substation. The protection consists of a trip coil connected between the star point of a 3-phase 4-wire system and earth. This trip coil is only operated by earth currents and can be of very low operating value, say 10 or 20 amperes. It should be fitted with a time-delay action so that any local fuses will operate more quickly, and it must be wound to ensure that it will not be burnt out even if the maximum possible fault current is passed. It must be borne in mind that to protect a 3-phase 4-wire l.v. overhead line fully we must cover the rare case of phase fault to earth. With a 125-kVA transformer a 250-ampere fuse or current setting is essential, and if the earth-plate resistance is 1 ohm then no operation is obtained, even if the resistance of the fault itself is ignored. With the scheme described above, earth-plate resistances up to 5 or 6 ohms are perfectly permissible.

My objection to multiple earthing is that if it were adopted we should still be faced with the necessity of obtaining many sound earths.

Mr. H. G. Taylor (*in reply*): It is very valuable to have the confirmation of Mr. Cameron Brown and Mr. Morgan that, as a result of 168 measurements in one case and of 200 in the other, they have reached the same conclusion as the Electrical Research Association—that in a very large proportion of cases the earth resistance is so high that even 5-ampere fuses cannot be blown. This situation amply justifies the investigation, and if the paper leads to any amelioration of such a serious condition, even though it may not lead to perfect protection, then it may be regarded as a forward step, and not a retrograde one as one of the speakers appears to think.

Mr. Melsom is clearly in favour of cables and more insulation; the former are economically impossible in rural areas and the latter, on the lines Mr. Melsom desires, is a counsel of perfection for domestic appliances.

Improvements could of course be made, but it is at least unlikely that appliances will ever be so constructed and provided with such insulation that the risk of contact between the current-carrying parts and the metal case can be ignored. I agree that where the floor of a room is an insulator it is safer not to earth appliances, but I think some investigation is necessary of the insulating properties of flooring materials. Mr. Melsom refers to the high voltage attained by neutral conductors in 3-phase and 3-wire systems. This is well known but, I think, only possible where a large resistance exists between the neutral point and earth at the substation and when a low-resistance earth fault occurs on one outer. In a properly-constructed protective multiple earthing system such a condition cannot exist; the possible voltage-rise of the neutral for various fault conditions is shown in Figs. 10 and 11 of the paper. I cannot see how the short-circuiting of any two conductors whether outers, or outer and neutral, can result in the potential of a neutral conductor, connected to earth at all consumers' premises and at the substation, rising to 200 volts above earth. We have been scared off protective multiple earthing for quite long enough by tales of high neutral voltages, and an attempt has now been made in the paper to examine the possibilities scientifically; it is not apparent that any important possibility of neutral voltage-rise has been overlooked.

Mr. Melsom does not explain what contacts and connections may corrode in protective multiple earthing systems which do not equally corrode, with equally serious results, in other methods of protection. With regard to cost, I am not aware that any proper comparison has yet been made. There are many complicating factors, and for equal protection the cheapest system in one place might be the dearest in another.

Dr. Radley, Mr. Grimmitt, and Mr. Fennell, together answer Mr. Frost's point about interference from long distributors. The problem of the rural system which is partly overhead and partly underground is being further considered by the Electrical Research Association.

Mr. Gilbert argues from the standpoint that protective multiple earthing is inherently bad and that the only satisfactory form of protection in all circumstances is the earth-leakage circuit-breaker. Such an attitude induces the presentation of all the facts relative to the disadvantages of the earth-leakage circuit-breaker in an attempt to correct the balance and enable a true view of the situation to be obtained. If this leads to an emphasis of the disadvantages it should not be regarded as a condemnation of a very useful protective device, the effectiveness of which is set out in some detail in the paper, but rather as an attempt to ensure that harm is not done to the cause of earth-leakage circuit-breaker protection by exaggerated claims as to its efficacy and by overlooking its limitations. Real progress in minimizing the chances of dangerous shocks will only be made by facing the facts and dealing with the situation as seems necessary—not by condemning one method root and branch and regarding another as perfect. The truth is that both methods have advantages and disadvantages, and, these being presented, it is for the engineer to choose the method most suitable for his own requirements. But the full facts must be presented—unpalatable though they may be.

Coming now to Mr. Gilbert's very lengthy criticism, it is perhaps pertinent to remark that Mr. Gilbert was a member of the Committee responsible for the Report and that many of his points have therefore been considered previously. The formula he gives for tripping current is exact; the formula in the Report is approximate, but the difference is small, being only 8 % when the resistance of the fault plus that of the earth electrode is equal to the impedance of the trip coil. As the ratio $(R_f + R_e)/Z_c$ increases, the difference becomes less. Fig. 4 was intended for use and the figure of 3 200 ohms was obtained from it; I am not surprised that the calculated value is 3 400 ohms, though I thank Mr. Gilbert for drawing attention to the fact. Mr. Gilbert is correct in stating that, in the example taken, a voltage of 72 only occurs on the metal-work when the fault resistance is zero. However, I do not think the error deserves the qualification "extremely serious" since it is only an example of the use of Fig. 4, and in any case it is not unusual for the fault resistance to be zero; in fact, one cannot safely assume any other value for it.

With regard to Fig. 4, I have shown above that to neglect the reactance of the trip coil has negligible effect; to include it involves some assumption being made as to the ratio of the reactance to the resistance of the trip coil; trip coils having 1 000 ohms impedance are not unknown; at the E.R.A. we have two of reputable make and recent construction with impedances over 1 100 ohms. Fig. 4 which, apart from the approximation stated above, is correct as it stands, may not give the most useful information; it indicates whether the trip coil will operate or not. Possibly it is more useful to show the actual voltage between the metal-work and earth in the way Mr. Gilbert shows it in Fig. B. Complete curves on these lines are being prepared by the E.R.A. for incorporation in a supplementary Report; but they do not show only the favourable case of a trip coil operating at 15 volts, as in Fig. A. The question of the influence of fault resistance is also receiving wider consideration, and it is not anticipated that the result will be altogether to the advantage of the earth-leakage circuit-breaker.

I thank Mr. Gilbert for drawing attention to an omission in Recommendation (iii). This has been rectified for the *Journal*.

With regard to the disadvantages of earth-leakage circuit-breakers set out on page 766: (i) cannot be advanced against ordinary earthing or protective multiple earthing since fuses are required throughout the installation for overload protection, quite irrespective of earth-fault protection, whereas the types of earth-leakage circuit-breakers under consideration provide only earth protection and are used in addition to fuses. With reference to (ii), it is admitted that it may be an advantage that the test-key checks the continuity of the wiring, but a limitation, if not a disadvantage, is that it does not check the whole of it. If the claims made for the test-key were more precise, it would be unnecessary to draw attention to the fact that it does not do all that is frequently inferred. Some engineers regard no test-key as preferable to one which only provides a partial

test and which may so give rise to a false sense of security. Furthermore, a press-key involves a spring-loaded point-contact always in the trip-coil circuit, and the possibility of corrosion giving rise to a thin insulating film at this point after some years, is not negligible. With regard to disadvantage (iv), I do not approve of such large leakage currents as may occur with cooker hot-plates, but that makes no difference to the fact of their existence with plates made by well-known firms, and we are informed that they cannot be avoided when the hot-plates are over-run or first switched on after a long idle period. Mr. Gilbert may be correct in saying, in reference to disadvantage (v), that the leakage circuit-breaker will operate, but this does not help the individual if his resistance to earth is so low that at voltages slightly less than those required to operate the circuit-breaker sufficient current can pass through his body to give him an unpleasant shock. A typical case occurs where the individual's body and earth resistance combined is 5 000 ohms, the fault resistance 4 000 ohms, the trip coil impedance 250 ohms, and the earth-electrode resistance 1 000 ohms. The voltage across the trip coil is then less than 10 (it may not operate until the value is 15) and the current through the body is about 9 mA—a quite unpleasant value.

I am sorry that Mr. Gilbert objects to the tests on earth-leakage circuit-breakers shown in Table 1; he was anxious that the tests should be done (since multiple-earthing tests had already been made); the issue of the Report was delayed for these tests, and if the results are not as good as Mr. Gilbert hoped, it is, perhaps, unfortunate. At the time there was no other system in this country using earth-leakage circuit-breakers on which tests could be made.

Continental experience with regard to the operating time of distribution-system fuses is different from British; in any case special attention to this point is called for, in the Report, where protective multiple earthing is used.

Recommendation (v) on page 778 is specially drafted to draw attention to the habit of using an earth-leakage circuit-breaker for a cooker only and of leaving the remainder of the exposed metal-work in an installation totally unprotected. The only experiments which have been made on earth-leakage circuit-breakers were conducted in the Dumfries area. We were not given to understand that these circuit-breakers were by any means unusual, but admittedly they were obtained from a number of different sources, and considerable credit is due to Mr. J. S. Pickles of the Dumfries County Council Electricity Department for being the first to install earth-leakage circuit-breakers on any considerable scale.

I do not think that the corrosion of earth electrodes in parallel has a serious bearing on protective multiple earthing, and Mr. Gilbert is wrong in suggesting that electrolysis from this source is in any way responsible for the decision to abandon multiple earthing in parts of Australia. Electrolysis, it is true, had some influence on the decision, but it was electrolysis due to stray currents from the suburban railway systems—a factor of very different magnitude. With regard to areas having both underground cables and overhead lines, I have already indicated that tests are to be made at a later date, but meanwhile it is of some significance to point out that several villages in Lancashire, where such conditions exist, are operating quite satisfactorily with protective multiple earthing.*

The major disadvantage of the earth-leakage circuit-breaker which has hindered its more general adoption is the possibility that it will be installed in a damp situation, will be adversely affected by the atmosphere, and eventually, after a number of years of inactivity, will be found incapable of operating when required. Such a view may be unjustified, but we have no experience to prove it. The alternative is effective maintenance, and the possibility of this falling on the supply undertaking is not viewed favourably by supply engineers. Mr. Fennell draws attention to this point, and also to the relative safety of single-point and multiple earthing. A system which gives at least a 5-times improvement over the present system of protection is one which merits serious consideration, without worrying too much about whether it is perfect.

Mr. Swan would have found he could obtain an earth resistance of much less than 1 ohm if he had buried his 90 yards of $0\cdot1$ sq. in. copper in, say, three radial trenches 30 yards long, instead of in a circle 9 ft. in diameter.

I appreciate Mr. Cameron Brown's comments about the gravity of the situation. In the event of a serious fault it is unlikely that some fuse will not blow in a protective multiple earthing system, even if the consumer has substituted a nail for his sub-circuit fuse, in view of the very low resistance provided by the metallic return. If no fuse blows, then the voltage on frameworks will be determined by the relative impedances of the line and neutral conductors and the degree of displacement of the neutral point. A 10-ohm impedance for a low-voltage distribution is very much higher than would occur in any system using protective multiple earthing, which is only recommended when the conductors have a section of $0\cdot05$ sq. in. Steps are being taken for preliminary use of protective multiple earthing on the lines suggested by Mr. Cameron Brown.

Mr. Grimmitt's valuable contribution to the discussion does not call for any comment. The answer to Dr. Radley's last question involves legal arguments of some length, but they are available and any who are sufficiently interested might be able to obtain them on application to the Electricity Commissioners.

Mr. Wood has not quite got the whole story in respect of the voltage on metal frameworks. He has omitted to take account of the fact that other consumers near the substation obtain the same voltage on their metalwork as occurs on the neutral at the substation. Furthermore, the consumer's earth resistance is in parallel with all those of his neighbours on the same side of the true neutral point. The matter is dealt with in some detail in Figs. 12 and 13 of the Report.

I do not agree to the implication of the first line of the fourth paragraph of Mr. Wood's comment that earth-leakage trips are a great deal better than multiple earthing. As I have already indicated, there are advantages and disadvantages in both methods. It is hoped

* *Electrical Times*, 1937, vol. 92, p. 259.

to set these out in considerable detail at a later date in an E.R.A. Report in order that all points may be taken into account in reaching a decision as to the most satisfactory method in any given set of conditions. The picture which Mr. Wood conceives of consumers obtaining shocks from all their apparatus and seeing open sparking is, I think, a little overdrawn. The possibility of any such occurrence is very unlikely. I think it is better on balance that the connection of the earth-continuity conductor to the neutral should be as shown in Fig. 7, since the consumer's earth resistance may happen to be a very low one on which considerable reliance is placed for maintaining a low neutral potential and the possibility of this being disconnected might be a disadvantage. Experience may be the best guide on this matter.

There is a very appreciable disparity between what Mr. Raphael regards as a safe current and what is generally recognized by leading authorities in many countries as a safe value. It is usually considered—and there is considerable supporting evidence—that currents above 25 mA may be fatal. Perhaps Mr. Raphael is referring to high-frequency currents or currents through non-vital parts of the body. I am very glad to have Mr. Raphael's correction about the originator of the earth-leakage circuit-breaker.

I thank Dr. Whitehead for his comments on the important question of radio-interference suppression, and also Mr. Siviour for his confirmation of the absence of broken overhead conductors. Mr. Bartholomew makes a good point about the unsuitability of protective multiple earthing for direct-current systems.

Mr. Morgan refers to the burning-out of trip coils owing to lightning, but I understand that this may be overcome by using a larger wire for the coil. The criticism of earth-leakage circuit-breakers at the substation is pertinent. Presumably this refers to the use of the coil in parallel with the main earth, whereas the description given by Mr. Hill of a substation earth-leakage circuit-breaker refers to one in which the trip coil carries the total fault current—a rather different proposition and one which seems to be new.

DISCUSSION ON "CONTROL ROOMS AND CONTROL EQUIPMENT OF THE GRID SYSTEM"*

THE AUTHOR'S REPLY TO THE DISCUSSIONS BEFORE THE TRANSMISSION SECTION AND THE NORTH-EASTERN CENTRE (SEE PAGES 619–624).

Mr. J. D. Peattie (*in reply*):

General.

The essential feature in the success of any control system—co-operation between those using it—is clearly set out in Mr. Johnstone Wright's remarks, and referred to by other speakers. The equipment described in the paper is only a means for assisting those co-operating in control.

The organization of control work, referred to by Mr. Winfield, to meet normal and abnormal conditions is outside the scope of the paper, which is confined to a description of the rooms and equipment. These have been provided for a definite purpose—the control of the grid and its associated generating stations. I agree with Mr. Winfield and Mr. Swangren that a different layout and equipment may be more appropriate for distribution control, which may also call for remote operation of switchgear.

I do not feel that it is possible at the present stage of rapid development to lay down any ideal arrangement of control. Each problem should be studied individually and advantage taken of all the latest developments in communication. Generally speaking, the aim should be to provide automatic equipment which will carry out economically and reliably as much as possible of the routine work, and keep continuously before those exercising control a clear, concise picture of the essential factors. Ample provision should be made for expansion.

Control Buildings.

Mr. Gregory and Mr. Rowan draw attention to features of design which in the past have received too little attention. While I am in general agreement with their remarks, it is by no means easy to satisfy the various tastes of those who have to work in the control rooms. Now that suitable enamels and synthetic products are available in a wide range of pleasing colours, there seems little reason for retaining the more formal but depressing black and nickel finish which was a feature of older operating and control rooms. Primrose and pale green have been extensively used in the Board's control rooms. The London mosaic diagram referred to by Mr. Swangren has a pale green base.

I agree with Mr. Byng and Mr. Linstow that the circular or oval room has advantages over the rectangular room, particularly if indicating devices are mounted round the walls. The advantages are not so great if the essential equipment is concentrated on the control desk, and in any case they have to be considered in relation to site restrictions and cost. The areas of the London and

* Paper by Mr. J. D. PEATTIE (see page 607).

Bristol control rooms are not equal, as suggested by Mr. Linstow. Actually the control, relay, and battery rooms in London occupy over twice as much floor space as at Bristol.

The special requirements referred to by Mr. Stedman hardly come within the scope of the paper, but they have not been lost sight of. Ample emergency battery lighting is provided at all centres.

Communication System.

It is difficult to give, as suggested by Mr. Linstow and Mr. Stedman, an accurate measure of the standard of reliability of the Post Office lines. Despite the difficulties referred to by Mr. Chamney, the service, which is continuous over the 24 hours, is at least as high as the general level on the Post Office public system. The Board's views on this matter will be found in Mr. Johnstone Wright's remarks.

Mr. Bartholomew and Mr. Willoughby suggest duplication of channels. Such a step, which immediately carries with it a corresponding increase in annual costs, has only been considered necessary in a few special cases.

Mr. Stedman's questions regarding the permissible limits of voltage and current have been answered by Mr. Chamney.

There has been no experience of the Board's power circuits coming into contact with the telephone or supervisory circuits. The precautions insisted on by the Postmaster General make any such contact a very remote contingency indeed.

Telephones and Automatic Equipment.

The grouping of telephone keys referred to by Mr. McWhirter has been adopted to reduce the number of keys required. Instruments with the usual automatic dials are also used for the same purpose.

The use of teleprinters as suggested by Mr. Byng has been considered from time to time, but under present conditions the additional service likely to be obtained does not appear to warrant the extra cost.

I am indebted to Mr. Sykes for pointing out certain details regarding the equipment and the communication circuits which were omitted from the paper.

Metering.

I agree with Mr. Linstow and Mr. Swangren on the advantages of continuous metering. As in every phase of the problem, service has to be considered in relation to cost, and for this reason continuous metering has only been provided on the more important circuits.

The use of the Board's integrating equipment for initiating remote indications of generator loads is criticized by Mr. Sykes. It was adopted for reasons of convenience and economy and has not, in fact, interfered in any way with the primary function of the integrating meters.

Frequency and Time Control.

So far, automatic frequency and time control referred to by Mr. Linstow have not been found necessary, but experiments are in progress with equipment developed for this purpose.

Miscellaneous Equipment.

Three short-circuit-calculating tables referred to by Mr. Peterson have been provided at the London and Manchester control centres. Two of them are built specially for the two systems in question. The third is a universal equipment which can be used for more general studies.

Reliability.

I agree with the remarks of Mr. Byng and Mr. Swangren regarding the reliability of the automatic equipment, including valves. The provision of suitable control equipment is essentially a communication problem, and it is not really surprising that apparatus developed as a result of many years' experience in general communication work should prove successful when used for this particular purpose. Routine maintenance, as of all engineering equipment, is essential, but so far has been quite normal.

REPORT OF THE COUNCIL FOR THE YEAR 1936-1937, PRESENTED AT THE ANNUAL GENERAL MEETING OF THE 6TH MAY, 1937

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REPORT

The Council, at the Sixty-Fifth Annual General Meeting of The Institution of Electrical Engineers, present to the members their Report for the year 1936–37, covering approximately the period from the 1st April, 1936, to the 31st March, 1937.

The Council desire once more to thank the many members who, by service on its numerous committees and in many other ways, contribute so materially to the efficiency of The Institution in carrying out the objects set out in its Royal Charter of Incorporation.

(1) MEMBERSHIP OF THE INSTITUTION

The changes in the membership since the 1st April, 1936, are shown in a Table included in Appendix A.

The following Table shows the net growth of membership for the last 10 years:—

Year	*Membership*	*Increase*
1928	13 043	396
1929	13 561	518
1930	14 200	639
1931	14 670	470
1932	14 884	214
1933	15 149	265
1934	15 619	470
1935	16 150	531
1936	16 788	638
1937	17 399	611

(2) PATRON OF THE INSTITUTION

The Council record with great pleasure that following upon the granting by King Edward VIII of his Patronage to The Institution in May, 1936, a Memorandum was received in December, 1936, from the Keeper of the Privy Purse stating that His Majesty King George VI was pleased to intimate to those Societies and Institutions which had recently been granted Patronage by King Edward VIII that they might continue to show the Sovereign as their Patron during the present Reign, unless otherwise notified.

(3) CORONATION

The Council are participating with other engineering institutions and societies in the preparation of a Joint Congratulatory Address to His Majesty King George VI on the occasion of his Coronation.

In response to an invitation received from the Earl Marshal through Norroy King of Arms, the President has been nominated by the Council to attend the Coronation Ceremony in Westminster Abbey as the representative of The Institution, and he has now received the Royal Command to be present at the Ceremony and also an invitation to the Review of the Fleet at Spithead on 20th May.

(4) HONORARY MEMBER

The Council have pleasure in recording that, as announced at the Ordinary Meeting on the 21st January, 1937, they have elected Dr. Alexander Russell, M.A., D.Sc., LL.D., F.R.S., Past-President, to be an Honorary Member of The Institution.

(5) FARADAY MEDAL

The fifteenth award of the Faraday Medal was made by the Council to Professor André Blondel (Honorary Member).

(6) HONOURS AND DISTINCTIONS CONFERRED ON MEMBERS

G.C.V.O.

Mountbatten, Comdr. The Rt. Hon. Lord Louis, K.C.V.O., R.N. (Associate Member).

Knighthood.

Gresley, Herbert Nigel, C.B.E., D.Sc. (Member).
Lee, Lieut.-Col. Albert George, O.B.E., M.C. (Member).

C.B.E.

Hippisley, Comdr. Richard John B., O.B.E. (Member).

O.B.E.

Yorke, John Paley, M.Sc. (Associate Member).

(7) DEATHS

The Council regret to have to record the death of the following 93 members of The Institution during the year:—

Honorary Member

Thomson, Elihu, D.Sc.

Members

Ainsworth, R.	Holroyde, A. G. C.
Aspinall, F. B.	Johnson, T. B.
Beales, M.	McLaren, D. E.
Brain, O. W.	Nielsen, F. C. C.
Burgess, A. E. C.	Nott, H. A., M.B.E.
Burstall, H. R. J.	Powell, D. T.
Byng, M.	Prideaux, W. H. C.
Coleman, A.	Risch, G. H. C.
Cowper-Coles, S. O.	Robertson, J. A.
Dallas, J. D.	Robins, W. H.
Fleming, E. G.	Rosher, N. B., O.B.E.
Forbes, Prof. G., M.A., F.R.S., F.R.S.E.	Rutherford, W.
	Sillar, A. M.
Ghosh, S. N.	Taylor, J.
Girdlestone, J. O.	Webb, G. A.
Hollingsworth, E. M.	Wilson, Henry.

Associate Members

Almers, C. L.	Leigh, A. J.
Angus, H. W.	Lynn, S.
Ashlin, F. J. W.	Macdonnell, Prof. A., B.A.
Barnes, W. A.	Martin, T. N.
Botting, R. F.	Petavel, Sir J. E., K.B.E., D.Sc., F.R.S.
Bridger, F. R.	
Brodie, W.	Place, J.
Brownjohn, W. H.	Pritchard, F.
Callender, G. G., B.E.	Rhodes, E. H.
Cardin, E.	Roach, C. G.
Davis, A.	Robinson, P., B.Sc.
De Albuquerque-Maranhao, A. de O.	Sandys-Ball, C.
	Schofield, F. E.
Edmondson, F.	Seaborne, W.
Flint, E. W.	Soutter, A. C.
Gear, J. I.	Stancombe, T. R.
Girdlestone, H.	Stephens, R. D.
Hesketh, E.	Stocken, A. L.
Hunt, F. C., M.B.E.	Tucker, V.
Jolley, A. C.	Turner, W. E.
Lauchlan, G.	Winn, J. P.

Companions

Cameron, Major Sir M. A., K.C.M.G.	Nash, Sir P. A. M., K.C.M.G., C.B.

Associates

Garnett, A.	Malan, E. de M.
Garnett, H. S.	Parker, W. A.
Hillman, R. V.	Skinner, E.
Lucas, F. R.	Williams, W. R.

Graduates

Kirsten, K. H., B.Sc.	Rule, R.
Krishnamurthy, K. V., M.Sc.	Seagrave, M.
	Smith, G. P.
Pask, A.	Willis, W. H., B.Sc.(Eng.).

Students

Carruthers, B. H.	Ross, A. D.
Edenborough, J. D. (Miss).	Whyman, D. H. R.

(8) EXAMINATIONS

Graduateship Examinations were held for a total of 630 candidates in May and November, 1936, in London, Belfast, Birmingham, Cardiff, Dublin, Glasgow, Loughborough, Manchester, and Newcastle-on-Tyne, and also, in November only, in Australia, Ceylon, Egypt, Federated Malay States, Gibraltar, India, New Zealand, Nigeria, Shanghai, and South Africa.

Examinations in English only were also held in May and November, 1936, at various centres in Great Britain for 333 holders of National Certificates in Electrical Engineering.

In addition, 13 candidates over 30 years of age were permitted to fulfil the educational requirements for Associate Membership by the submission of satisfactory papers or theses in lieu of the Examination.

No award of the Page Prize was made this year. This prize is offered for the best paper or thesis submitted in lieu of the Examination, provided one of sufficient merit has been received to justify an award being made.

(9) NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING

England and Wales.—In 1936 the Joint Committee, representing the Board of Education and The Institution, was associated with the final examinations of 202 courses at colleges and schools in England and Wales, approved in connection with the above certificates and diplomas.

The final examinations were held during the summer and the number of awards was as follows:—

735 Ordinary Certificates;
374 Higher Certificates;
53 Higher Certificates endorsed;
20 Ordinary Diplomas;
15 Higher Diplomas.

Scotland.—In conjunction with the Scottish Education Department, The Institution was associated with 18 courses in Scotland during the year under review.

The final examinations were held during the summer, and the number of awards was as follows:—

28 Ordinary Certificates;
18 Higher Certificates;
12 Higher Certificates endorsed;
12 Higher Diplomas.

(10) SCHOLARSHIPS

The following Scholarships have been awarded by the Council during the Session:—

Ferranti Scholarship
(Annual Value £250; tenable for 2 years.)
W. E. Harper (Birmingham University).

Duddell Scholarship
(Annual Value £150; tenable for 3 years.)
P. Hargreaves (Lower School of John Lyon, Harrow).

Silvanus Thompson Scholarship
(Annual Value £100, plus tuition fees; tenable for 2 years.)
L. S. Anand (North-Western Railway, India).

William Beedie Esson Scholarship
(Annual Value £120; tenable for 2 years, renewable in approved cases for a third year.)
No award.

Swan Memorial Scholarship
(Value £120; tenable for 1 year.)
D. H. Thomas (Metropolitan-Vickers Electrical Co., Ltd.).

David Hughes Scholarship
(Value £100; tenable for 1 year.)
W. H. Penley (Liverpool University).

Salomons Scholarship
(Value £100; tenable for 1 year.)
E. F. O. Masters (City & Guilds College, London).

Paul Scholarship
(Annual Value £50; tenable for 2 years.)
No award.

Thorrowgood Scholarship
(Annual Value £25; tenable for 2 years.)
L. G. Leaton (Southern Railway Co.).

War Thanksgiving Education and Research Fund (*No.* 1)
No award.

All the Scholarships mentioned above, and grants, may be awarded annually with the exception of the Paul and William Beedie Esson Scholarships, which are awarded in alternate years only. When an award of the latter scholarship is renewed for a third year, however, the next award is deferred for a year.

(11) INSTITUTION BUILDING

As in past years, the use of The Institution's premises has been granted without charge to a number of kindred societies in connection with their meetings, and 234 such meetings have been held during the past year.

The growing demand by The Institution itself for accommodation for meetings makes it increasingly difficult to grant the use of the lecture theatre and rooms to other societies as readily as in the past.

It was mentioned in the last Annual Report that improvements to the heating and ventilating plant in the building were contemplated. This work was duly carried out during the summer of 1936, the hand-fired solid-fuel boilers being removed and replaced by an electrically-heated water system, automatically controlled on the off-peak thermal-storage principle.

A completely new system of ventilation for the lecture theatre has also been installed, fresh air, delivered across fin-tube heating-coils (water) through sheet-metal ducts, being drawn into the theatre at high level by means of an inlet plenum fan, and the vitiated air being drawn off by the extract fan through gratings at floor-level. The air-heating units, controlled by thermostats and served by the thermal-storage plant, are capable of raising the temperature of the incoming ventilating air to 75° F. from an initial temperature of 32° F. The old outfit, consisting of a mechanical extractor system of ventilation, has been left undisturbed and can be used, if desired, on occasions when the audience is small.

(12) UNAUTHORIZED USE OF MEMBERSHIP INITIALS

There have been several cases during the past year of the use, by unauthorized persons, of initials or descriptions implying that they were members of The Institution. It has been possible in each case to ensure the discontinuance of the practice by the person concerned without the necessity of taking legal action.

(13) MEMBERS OF LONG STANDING

The Council recently adopted a recommendation of the Finance Committee that as soon as a member of any class has attained his 50th year of membership of The Institution he may, if he so desires, cease to pay any further annual subscriptions. The List of Members contains the names of 72 members of 50 or more years' standing, but of these some are Honorary Members, and others are already exempt from payment of subscriptions as a result of their having compounded for life or on account of their coming within the scope of the existing rule relating to retired members which has been in operation for some years. There remain 22 members who are eligible this year and their attention has been drawn to the new rule.

It should be made clear that this new rule is supplementary to the existing rule of the Council referred to above, which provides that any Corporate Member who has reached the age of 60 and has retired from the practice of his profession or business may apply to the Council to remit his future annual subscriptions, provided that his membership of The Institution has been continuous for at least 25 years.

(14) MEETINGS

During the past 12 months, 530 meetings were held in London and at the Local Centres by the members, the Council, and the various Committees. A detailed statement is given in Appendix B.

The average attendance at the 14 Ordinary Meetings held in London was 262, compared with 246 for the Ordinary Meetings last Session.

(15) PREMIUMS

The Premiums awarded by the Council for papers read at meetings or accepted for the *Journal* will be announced* about the time of the Annual General Meeting.

(16) LOCAL CENTRES AND SUB-CENTRES

The Council record their gratification at the well-sustained activities of the Local Centres and Sub-Centres and express their keen appreciation of the extent to which the work of these branches of The Institution assists in maintaining its prestige and influence.

* See *Journal I.E.E.*, 1937, vol. 80, p. 677.

The Council also take this opportunity of expressing their grateful thanks to the Chairmen of Local Centres for their regular attendance in London at the meetings of the Council, thereby ensuring co-operation between the latter and the Centre Committees.

The President and the Secretary have attended functions at the Centres at Birmingham, Bristol, Glasgow, Leeds, Liverpool, Manchester, and Newcastle-on-Tyne (Secretary only), as well as at the East Midland, Hampshire, Sheffield, and Tees-Side Sub-Centres, and they hope to be present at meetings in Belfast and Dublin in April. Through indisposition the President was unable to visit Newcastle-on-Tyne.

On the occasion of each of his visits up to date, the President addressed the members present and was particularly impressed by the evidence of continued development, and also of appreciation by the members of the opportunities for discussion and intercourse afforded by the local programmes, full details of which are contained in the Annual Reports presented each year to the members in the respective areas. He was also greatly impressed by the good relations that exist in all parts of the country between members of the Centres and members of kindred institutions and associations.

Local technical libraries, the setting up of which was first approved by the Council in 1922, are now in existence at Birmingham, Dublin, Leeds, Liverpool, Loughborough, Manchester, Middlesbrough, Newcastle-on-Tyne, Portsmouth, and Southampton. Full details of the arrangements for borrowing or referring to the books at these libraries can be obtained on application to the local Hon. Secretaries.

The Council last Session approved the formation of a Sub-Centre in Northern Ireland, to operate directly under the Council, and the Sub-Centre Committee are to be congratulated on the very successful programme carried out during the present Session.

The Annual Meeting of the Hon. Secretaries of Local Centres and Sub-Centres was held in London on the 4th February, 1937, the date of the Annual Dinner, when a useful discussion took place on matters of organization and administration.

It is with deep regret that the Council record the death, on the 30th January, of Mr. Joseph Taylor, who had been Honorary Secretary of the Scottish Centre for the past 23 years. During his long period of office Mr. Taylor rendered most valuable service to The Institution in advancing its interests in Scotland.

(17) ACTIVITIES OF OVERSEAS MEMBERS

The Overseas Activities Committee of the Council are very gratified at the continued progress of The Institution overseas. Details have been received of meetings at which papers have been read and discussed, and also of social gatherings which have been arranged by the Argentine and China Local Centres and by the Local Committees in New South Wales, Queensland, Victoria, Western Australia, and Ceylon, and at Bombay, Calcutta, and Lahore.

In some instances papers already read in London have been read and discussed, and papers have also been written and presented by local members.

The scheme of co-operation with other institutions initiated in Argentina and China has further developed and is operating very satisfactorily.

The fifth Annual Conversazione and Reunion of members from overseas, and their ladies, was held in The Institution building on Wednesday, 15th July, 1936. The total attendance was about 130, and the arrangements were similar to those made for the four previous functions. An account of the proceedings was published in the *Journal* for August, 1936 (vol. 79, page 238).

(18) LOCAL HONORARY SECRETARIES ABROAD

During the Session the Council received the resignations of Mr. C. C. T. Eastgate, Local Honorary Secretary for India since 1920, and Mr. J. Grosselin, Local Honorary Secretary for France since 1921, and have tendered cordial thanks to these members for their zealous work on behalf of The Institution. In their places the Council have appointed Mr. K. G. Sillar (India) and Mr. P. M. J. Ailleret (France).

(19) WIRELESS SECTION

The membership of the Wireless Section is now 860. Seven meetings have been held during the past year, at which nine papers were read. In addition, eight papers have been published or accepted for publication in the *Journal*. The average attendance at the meetings was 151, compared with 196 for last session, but the interest of the papers read and the quality of the discussions have well maintained the standard of previous sessions.

The Section Informal Meetings, which were introduced in January, 1935, have continued to be well supported. Three meetings have been held, and the average attendance was 137, which compares with 280 during the previous session.

(20) METER AND INSTRUMENT SECTION

The membership of the Meter and Instrument Section is now 669. Eight meetings of the Section have been held during the past year, the average attendance being 105, which compares with 81 during the preceding 12 months. The meetings have included one which has been devoted to an Informal Discussion. The practice, which was started two sessions ago, of arranging demonstrations of apparatus to accompany papers whenever practicable was continued this session and greatly added to the interest and success of the meetings.

The Committee wish to remind the members that short demonstrations will be welcomed of apparatus and processes which come within the scope of the Section but which do not necessarily relate to the subject matter of the paper being read on the same evening.

The Summer Visit for 1936 was held in Oxford and district on Saturday, 2nd May, and about 150 members and ladies took part. The programme included a visit to the works of Messrs. Morris Motors, Ltd., at Cowley, followed in the afternoon by a tour of inspection of some of the colleges and a river trip over the University rowing course.

The Section held its Annual Dinner on the 13th November, 1936, the attendance being 190.

(21) TRANSMISSION SECTION

The Transmission Section now has a membership of 1 662. Seven meetings have been held during the past year, the average attendance being 95, compared with

80 during the preceding 12 months. Papers of high merit have been read, the discussions being interesting and well sustained.

The Summer Visit of the Section was held in Cheshire on Friday, 15th May, 1936, when over 100 members and ladies took part. The party assembled at Winsford Station at 12.15 p.m., and the programme commenced with an inspection of the Winsford Meadowbank works of the Salt Union, a number of the party going down the Rock Salt Mine. The remainder of the day was devoted to a tour of the surrounding country, features of the special system of rural distribution of the Mid-Cheshire Electricity Supply Co., Ltd., being inspected *en route*. The visit concluded with tea at the Marbury Hall Country Club as the guests of the Mid-Cheshire Co., who also kindly provided the motor-coach transport during the day, and to whom the thanks of the Section Committee are due.

An innovation in the activities of the Section this year was a week-end visit to Paris by the invitation of the Société Française des Électriciens. The visit was held from the 17th to the 20th July, 1936, 36 members taking part. The morning of the 18th was devoted to a general discussion between members of the party and some English-speaking French engineers on generation and distribution, tariffs, etc. This discussion took place at the Office Central Électrique, where the showroom of the Compagnie Parisienne de Distribution d'Électricité was seen. In the afternoon the Ampère Substation and the St. Denis II power station of the Société d'Électricité de Paris were inspected. On the 19th the power station of the Société de Transport d'Énergie de L'Île de France at Creney was visited, the party leaving Paris that night for London.

The Committee of the Section record their appreciation of the kindness and hospitality with which the party were received during the visit, and of the assistance rendered by Mr. P. M. J. Ailleret, General Secretary of the Société Française des Électriciens and The Institution's Local Honorary Secretary for France, who made all the necessary arrangements in France for the visit.

The Annual Conversazione and Dance of the Section took place on Wednesday, 4th November, 1936. As in previous years, this was a very successful function, and was attended by 217 members and guests.

Visits to works were inaugurated last year as part of the activities of the Section, and a successful visit has been held this session to the Willesden works of the British Thomson-Houston Co., Ltd. This took place on Wednesday afternoon, 17th March, 1937, when between 60 and 70 members were present. Thanks have been accorded to the company for the excellent arrangements made for the reception of the party.

(22) INFORMAL MEETINGS

Eleven meetings have been held during the year, the average attendance being 72, as against 85 last year.

The Informal Meetings Committee again cordially invite members to write to the Secretary indicating subjects which they wish to suggest for discussion. Offers from members to open discussions will also be welcomed and carefully considered by the Committee.

The Council wish to remind the younger members, and particularly those who have not yet attended any of the meetings, that these are arranged primarily for them, with the object of their gaining experience in public speaking and thereby acquiring confidence to take part in the discussions on papers at the Ordinary Meetings.

The proceedings of the Informal Meetings are not reported by the Press, and only a brief précis of the discussions (prepared by a member of the Committee) is sent to the technical journals for publication.

(23) STUDENTS' SECTIONS

Full details have been given from time to time in the *Students' Quarterly Journal* of the programmes of meetings, visits to works, and social functions which have been carried out by the nine Students' Sections at London, Birmingham, Bristol, Glasgow, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, and Sheffield.

The actual membership of the nine Sections is in the aggregate 4 010, which includes 1 851 Graduates up to the age of 28, who are entitled under the Bye-laws to the same privileges as Students.

The "Students' Lectures" were delivered this Session by Mr. J. W. Thomas, LL.B., B.Sc.Tech., and Mr. J. N. Waite, who visited the places indicated:—

Lecturer.	*Subject.*	*Place.*
Mr. J. W. Thomas, LL.B., B.Sc.Tech.	"Law as it affects the Engineer."	London Birmingham Bristol Liverpool Manchester
Mr. J. N. Waite	"Engineering and Administration."	Edinburgh } Scottish Glasgow } Section Leeds Newcastle-on-Tyne Sheffield

The total attendances at the 10 lectures were approximately 480, compared with 680 for the 10 lectures given last Session. Although the lectures were greatly appreciated, it is felt that the attendances should be considerably higher, taking into account the total membership of the Sections. Arrangements have been made for Mr. J. W. Thomas and Mr. J. N. Waite to be the lecturers again next session, each to give the same lecture at the Sections which he did not visit during the present session. The Council hope that the lectures next session will receive greater support.

The sixth Annual Meeting of the Honorary Secretaries of the Sections was held in London on the 5th February, 1937, when a useful discussion took place on points of common interest.

The *Students' Quarterly Journal*, now in its seventh volume, continues to present a blend of articles of technical and general interest, and is quoted to an increasing extent at Students' Meetings. Owing to the transitory membership of the Students' Sections, it is necessary periodically to remind readers that articles are required, but in general the support has been such that the standard set in the early volumes has been well maintained.

Contact with the Sections is ensured by personal visits of the Editor. Those members who live too far away to attend meetings find the *Journal* enhances their interest in The Institution, its activities, and its traditions.

Senior members of The Institution are reminded that

copies of the publication can be obtained by them on payment of an annual subscription of 6s. The charge to the general public is 10s. per annum.

The London Students' Section followed up their successes of the two previous sessions by again winning the "Young" Trophy at a Sports Contest between the London Students' Section and the Students and Graduates of The Institutions of Civil and Mechanical Engineers. This contest consisted of cricket, tennis, and shooting matches, a full account of which was given in the September number of the *Students' Quarterly Journal*.

(24) REVIEWS OF PROGRESS

Continuing the series of reviews of progress in electrical engineering, which have appeared in the *Journal* each year since 1926, reviews on the following subjects have been published during 1937:—

Electric Traction.
Electrical Measuring Instruments (Scientific and Industrial).
Electricity in Mines.
Electrochemistry and Electrometallurgy.
Integrating Electricity Meters.

Arrangements have been made for reviews on the following subjects in 1938:—

Radiological and Electromedical Apparatus.
Tariffs.

(25) FARADAY LECTURE

The Faraday Lecture this Session was delivered by Mr. R. S. Whipple, who chose as his subject "Electricity in the Hospital." It was given at Bath, Birmingham, Liverpool, Loughborough, Manchester, and Newcastle-on-Tyne, and will also be given in Dublin, Dundee, and London, before the session closes.

The 6 Lectures so far delivered this session have been attended by an audience totalling approximately 4 260, of whom over 3 500 were non-members. The corresponding figures for 8 Lectures delivered in the previous year were 7 550 and 6 300 respectively.

(26) ANNIVERSARY CELEBRATIONS AND CONFERENCES

During the year under review, The Institution has been represented at Anniversary Celebrations and Conferences, etc., arranged by other bodies as shown in the following table:—

Name of Body.	*Nature and Date of Function.*	*Name of I.E.E. Representative.*
Association of Teachers in Technical Institutions	Annual Conference, Plymouth (30 May–2 June, 1936)	H. Midgley
Associazione Elettrotecnica Italiana	Annual Reunion, Rome (18–24 October, 1936)	L. Emanueli (Local Honorary Secretary for Italy)
National Smoke Abatement Society	Eighth Annual Conference, London (14–17 October, 1936)	H. C. Lamb C. D. Taite
Royal Sanitary Institute	Annual Congress, Southport (6–11 July, 1936)	E. Moxon
Svenska Teknologföreningen	75th Anniversary Celebrations, Stockholm (19 and 20 May, 1936)	J. S. Edstrom

In addition, letters conveying The Institution's good wishes were sent to the following bodies in connection with the occasions indicated:—

Czechoslovak Electrotechnical Association	18th National Annual Convention, Plzen (15–20 May, 1936).
Society for Founding Nikola Tesla's Institute	80th Anniversary Celebrations of the birth of Nikola Tesla, Belgrade (28–31 May, 1936).
Verein Deutscher Ingenieure	80th Anniversary Celebrations of the V.D.I. and 100th Anniversary Celebrations of the Darmstadt Technical High School, Darmstadt and Karlsruhe (25–27 May, 1936)

(27) SUMMER MEETING

In response to an invitation from the Committee of the Scottish Centre a Summer Meeting was held last year in Glasgow and the West of Scotland from the 15th to the 20th June, 1936, when 200 members and ladies took part. The programme commenced with a reception and dance at the Central Station Hotel on the evening of the 15th, and, on the 16th and 17th, visits were paid to the Galloway power scheme and the Renfrew works of Messrs. Babcock and Wilcox, a cruise on the Firth of Clyde, by invitation of the Company, being combined with the latter visit.

On the morning of the 18th, alternative visits were arranged to the following: The Alloa works of Messrs. Harland Engineering Co., Ltd.; the Clyde's Mill power station of the Clyde Valley Electrical Power Co., Ltd.; the Polytechnic Stores of Messrs. Lewis, Ltd.; the Bridgeton works of Messrs. Mavor and Coulson, Ltd.; the Scotstoun shipyard of Messrs. Yarrow and Co., Ltd. In the afternoon the party left Glasgow by motor coach for an excursion to the West of Scotland, the night being spent at Oban. On the 19th an all-day excursion took place, during which the new dams of the North British Aluminium Co., Ltd., at Loch Laggan were inspected. This excursion terminated at Callander, the meeting breaking up there the following morning.

The thanks of The Institution have been conveyed to the firms mentioned above, and the Council wish to place on record their hearty appreciation of the cordial and hospitable manner in which the party were received throughout the meeting. They also record their high appreciation of the work of the Committee of the Scottish Centre, particularly of Mr. J. B. Mavor, Chairman, and of the late Mr. Joseph Taylor, Hon. Secretary, whose work conduced so materially to the success of the meeting.

(28) ANNUAL CONVERSAZIONE

The Annual Conversazione was held on the 2nd July, 1936, at the Natural History Museum, London. The total attendance of members and guests was 2 158, compared with 2 008 in the previous year.

(29) ANNUAL DINNER

The Annual Dinner was held at Grosvenor House, Park Lane, London, on the 4th February, 1937, when

1 015 members and guests were present. An account was published in No. 484 of the *Journal*, April, 1937.

(30) LIBRARY

During the year, 494 books and pamphlets were presented to the Reference Library by members and others, and 103 volumes were purchased. The total number of readers for the year was 6 781, of whom 602 were non-members, as against 7 517 and 593 respectively in 1935–36.

Seventy new volumes were added to the Lending Library and 2 963 books were issued to 1 224 borrowers, the corresponding numbers for the previous year being 3 384 and 1 317 respectively.

Through the generosity of Mrs. B. A. Behrend, The Institution has received a collection of textbooks and a file of *Nature* which formerly belonged to Oliver Heaviside, F.R.S., and which are annotated by him, also some documents, including four autograph letters from O. Heaviside to the late Mr. B. A. Behrend.

(31) GIFTS TO THE INSTITUTION

The Council express their cordial thanks to the donors of the following gifts to The Institution:—

Donors.	*Gifts.*
Mr. H. F. D. Jacob	A specimen of the 275-kV overhead line from Boulder Dam to Los Angeles.
Mr. C. M. Mayson	A 150-ampere main switch (*c.* 1888).
Mrs. B. Ayrton Gould	A bas-relief portrait of the late Prof. W. E. Ayrton, F.R.S.
Mr. G. H. Nisbett	A collection of Nernst lamps and glowers.

(32) VISITING MEMBERS

The Council would like again to bring to the notice of members who intend to travel abroad that in certain countries reciprocal arrangements are in operation for the extension of privileges to visiting members. The sister Institutions concerned are:—

The American Institute of Electrical Engineers;
The Institute of Electrical Engineers of Japan;
The Norsk Elektroteknisk Forening;
The Société Française des Électriciens; and
The South African Institute of Electrical Engineers.

The privileges include attendance at meetings, library facilities, and such visits, excursions, etc., as may be in progress. The Secretary will gladly give letters of introduction to any members interested.

(33) PARSONS ANNUAL MEMORIAL LECTURE

As indicated in the last Annual Report, the first Parsons Memorial Lecture was, at the invitation of the Royal Society, given, in 1936, under the aegis of the North-East Coast Institution of Engineers and Shipbuilders. The Society invited the I.E.E. to sponsor the second lecture, to be delivered towards the end of 1937, and arrangements have been made for this fixture to be included in the arrangements for the first half of next Session. The Lecture will be delivered by Dr. Gerald Stoney, F.R.S. (Member).

(34) ALEXANDER GRAHAM BELL

Arrangements are being made with the Edinburgh Town Council for a memorial plaque to be placed in a suitable position at 16 South Charlotte Street, Edinburgh, to indicate that Alexander Graham Bell, the inventor of the electric telephone, was born at that address on the 3rd March, 1847.

(35) HISTORY OF THE INSTITUTION

The Council have decided to publish a History of The Institution. The work has been entrusted to Mr. Rollo Appleyard, and it is hoped that the book will be ready for publication within the next two years.

A great deal of relevant information suitable for inclusion in the book is already in the archives of The Institution, but it is felt that there must be many members of The Institution and others who have information in their possession, or can recall facts, which might be of assistance to Mr. Appleyard in making the work complete in every essential detail. The Council hope that those who have such information will communicate it to the Secretary at an early date.

(36) INTERNATIONAL ENGINEERING CONGRESS, GLASGOW, 1938

It has been decided to collaborate with other Institutions in according the support of The Institution to an International Engineering Congress to be held in Glasgow in 1938 on the occasion of the Empire Exhibition. The Congress, proposals in regard to which were first received from The Institution of Engineers and Shipbuilders in Scotland, will probably be held from the 21st to the 24th June, 1938. The Committee of the Scottish Centre are arranging their local Summer Meeting for 1938 in conjunction with the Congress.

(37) "SCIENCE ABSTRACTS"

The Physics volume of *Science Abstracts* for 1936 contains 5 716 abstracts, compared with 5 251 in 1935. The Electrical Engineering volume contains 3 525 abstracts, compared with 3 080.

A feature of the Annual Index to Section "A" (Physics) which has proved of considerable value since its introduction in 1934, is the inclusion of a "Supplementary Index of Apparatus and Instruments," in which the papers are classified under the names of the instruments and are arranged in alphabetical order.

Science Abstracts, which appears monthly in two sections, namely, Section "A" (Physics) and Section "B" (Electrical Engineering), consists of full abstracts from the leading scientific and technical journals and the proceedings of learned societies of the whole world, and presents in a form convenient for immediate reference a complete and concise record of the progress of physical science and electrical engineering. 1 346 members of The Institution subscribe to *Science Abstracts*, 770 subscribing to both Sections and 576 to Section "B," but the Council hope that in view of its exceptional value more members will become subscribers to the publication. It may be obtained, if ordered in advance, by Students of The Institution, as well as by Graduates up to the age of 28, at the special rate of 7s. 6d. per annum for both Sections, or 5s. for either the Physics or the Electrical Engineering Section, and by all other

members of The Institution at 20s. for both Sections, or 12s. 6d. for either Section alone, the rates charged to the general public being £1 15s. per Section, or £3 for both Sections.

(38) MODEL GENERAL CONDITIONS FOR CONTRACTS

The set of Model Conditions "A" for the supply of plant and materials and the execution of work connected therewith, for home contracts, last revised in April, 1929, is still under revision, and a new edition will be issued as soon as possible.

(39) REGULATIONS FOR THE ELECTRICAL EQUIPMENT OF BUILDINGS

The Wiring Regulations Committee have made considerable progress in the preparation of the Eleventh Edition. A number of Sub-Committees have been appointed to assist in the revision and in dealing with the numerous matters which arise from time to time in connection with the Regulations.

(40) REGULATIONS FOR THE ELECTRICAL EQUIPMENT OF SHIPS

The Ship Electrical Equipment Committee are continuing the revision of the Second Edition of the Regulations.

In view of the progress which has been made in recent years in the application of electricity at sea, both in electric propulsion and in general electrical installations on board ship, a special Sub-Committee has been appointed to investigate the proper maintenance of electrical equipment of ships, and the responsibilities, general qualifications, and status, of sea-going electricians.

(41) ELECTRICITY REGULATIONS

As indicated in the last Annual Report, a proof of a revised code of Regulations which was received from the Electricity Commissioners was duly examined during the Session by the Electricity Supply Regulations Committee. A report containing the Committee's recommendations was presented to the Council and approved for submission to the Electricity Commissioners. A revised code of Regulations, under the title of "Electricity Supply Regulations (1937)," has since been issued by the Commissioners.

(42) COMMITTEE ON ELECTRICAL INTERFERENCE WITH BROADCASTING

On the 2nd July, 1936, the Council received and approved the Final Report of the Committee and agreed that copies should be sent to the Postmaster-General, the Ministry of Transport, and the Electricity Commissioners. The full Report will be found in the *Journal* (vol. 79, p. 206).

A draft British Standard Specification for "Components for Use in the Suppression of Radio Interference from Trolley Buses and Tramways" was submitted to the Committee and was approved.

A suggestion by the Secretary of the British National Committee of the I.E.C., that the duties in connection with the Special International Committee on this subject should now be transferred to the Electrical Industry Committee of the British Standards Institution, was agreed to, and the transfer has now been effected.

(43) BENEVOLENT FUND

The Committee of Management of the Benevolent Fund of The Institution report that on the 31st December, 1936, the total assets of the Fund amounted to £27 371 14s. 4d. The donations and subscriptions to the Fund in 1936 amounted to £3 040 16s. in which amount are included the proceeds of Golf Competitions organized by the Mersey and North Wales (Liverpool) Centre (£170), the North-Western Centre (£95), and the Incorporated Municipal Electrical Association (£12 8s. 6d.). In addition to the foregoing, the Fund benefited by the surplus of £230 1s. 5d. on the Electrical Engineers' Ball for 1936, and gifts were received from the organizers of similar functions in the provinces (£65 from the South Midland Electrical Engineers' Ball, £15 15s. from the North-Western Centre, Manchester Engineers' Dance Committee, and £6 6s. from the South Midland Centre Students' Ball). A gift of £37 was contributed by the British Electrical Development Association, being part of the proceeds of two carnivals held at Newcastle-on-Tyne and Glasgow respectively. A donation of £105 was also received from the Association of Lancashire and Cheshire Electricity Undertakings. Full details are shown in the Accounts of the Fund for 1936 (see page 812).

In the course of 1936, grants were made in 73 cases, amounting to a total of £3 720 3s. 3d. In assisting these cases, the Fund also provided for the necessities of 86 dependants. During the last few years the annual totals of the grants made have shown such a marked increase that the expenditure is rapidly approaching the total revenue of the Fund.

The Council particularly desire to bring the Fund to the notice of all members of The Institution. At present 30 per cent of the members subscribe to the Fund, and the Council appeal to the remaining members to send donations or promises of annual subscriptions of any amount, which will be gratefully received.

The Committee wish to express great appreciation to the Local Honorary Treasurers for their efforts in stimulating an active interest in the Fund among the members in the Local Centres, and their valuable assistance in the investigation of applications.

Electrical Engineers' Ball.

The Ball, which was held at Grosvenor House, Park Lane, on Friday, the 5th February, 1937, was again most successful, and the Fund benefited by receiving the whole of the surplus of £244. Cordial thanks are due to the General and Executive Committees of the Ball and the stewards for their valuable assistance.

The Council and the Committee of Management of the Benevolent Fund wish to put on record their appreciation of the services rendered by the late Mr. A. M. Sillar over the long period from the year 1904 to the time of his death in March, 1937, as a member of the Ball Committee and during recent years as its Chairman.

(44) SUMMARY OF ANNUAL ACCOUNTS

Income and Expenditure.—The Surplus on the Revenue Account for the year ended 31st December, 1936, is £3 113 1s. 8d. This amount has been carried to the Balance Sheet, and compares with a surplus of £6 087 13s. in 1935.

Surplus of Assets over Liabilities.—Taking the investments at cost and The Institution building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

		£ s. d.
the Assets amount to:—		
Institution building and lease	73 028 6 10	
Investments, cash, etc.	139 476 15 3	
Stock of paper, libraries, and furniture ..	6 927 19 4	
		219 433 1 5
less Liabilities:—		
Trust Fund Accounts	315 2 4	
Sundry Creditors ..	6 165 1 4	
Repairs Suspense Account	3 900 18 4	
Subscriptions received in advance	378 4 11	
		10 759 6 11
leaving a surplus of		208 673 14 6
which in comparison with that for the year 1935, viz.		206 704 6 5
shows an improvement of		£1 969 8 1

Investments.—No investments were made during the year.

(45) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED

Appendix C (page 801) shows in diagrammatic form the organization of The Institution and the bodies on which it is represented.

APPENDIX A

Membership of The Institution

The changes in the membership since the 1st April, 1936, are shown in the following table:—

	Hon. Mem.	Mem.	Assoc. Mem.	Com.	Assoc.	Grad.	Stud.	TOTAL.
Totals at 1 April, 1936	16	1 991	6 562	103	1 355	3 952	2 809	16 788
Additions during the year:—								
Elected ..	1	1	136	7	81	295	783	1 304
Reinstated	—	3	10	—	6	4	12	35
Transferred to ..	—	71	301	—	7	375	—	754
Totals	1	75	447	7	94	674	795	2 093
Deductions during the year:—								
Deceased ..	1	31	40	2	8	7	4	93
Resigned ..	1	9	46	2	11	56	72	197
Lapsed ..	—	8	44	—	31	88	267	438
Transferred from ..	—	—	70	—	42	254	388	754
Totals	2	48	200	4	92	405	731	1 482
Net Increase								611
Totals at 1 April, 1937	15	2 018	6 809	106	1 357	4 221	2 873	17 399

APPENDIX B

Meetings

The following is a list of the meetings held during the past 12 months:—

Ordinary Meetings ..	14
Annual General Meeting	1
Annual General Meeting (Benevolent Fund)	1
Wireless Section ..	10
Meter and Instrument Section	9
Transmission Section	8
Informal Meetings ..	11
Council Meetings ..	14
Local Centres:—	
Irish	8
Mersey and North Wales (Liverpool)	13
North-Eastern ..	15
North Midland ..	12
North-Western ..	13
Scottish	11
South Midland ..	12
Western	12
Local Sub-Centres:—	
Dundee	6
East Midland ..	8
Hampshire ..	9
Northern Ireland ..	6
Sheffield	9
Tees-Side	8
West Wales (Swansea)	6
Students' Sections:—	
Bristol	5
Liverpool	11
London	11
North-Eastern ..	11
North Midland ..	12
North-Western ..	11
Scottish	13
Sheffield	8
South Midland ..	12
Committees:—	
Benevolent Fund ..	10
Electrical Engineers' Ball ..	5
Electrical Interference with Broadcasting (and Sub-Committees) ..	6
Committees—*continued.*	
Electricity (Supply) Regulations ..	1
Examinations ..	8
Finance	9
General Purposes (and Sub-Committees)	8
H.T. Conference, Paris (British National Committee)	1
Informal Meetings	7
Local Centres ..	3
Membership ..	9
Meter and Instrument Section (and Sub-Committees)	19
Model General Conditions	3
National Certificates (England) ..	3
National Certificates (Scotland) ..	2
Overseas Activities	3
Papers (and Sub-Committees) ..	10
Scholarships ..	2
"Science Abstracts"	1
Ship Electrical Equipment (and Sub-Committees)	11
Transmission Section (and Sub-Committees) ..	16
Wireless Section (and Sub-Committees)	17
Wiring Regulations (and Sub-Committees)	50
Other Committees	16
Total ..	530

APPENDIX C

THE INSTITUTION OF ELECTRICAL ENGINEERS

- Ordinary Meetings
- Wireless Section Meetings
- Meter and Instrument Section Meetings
- Transmission Section Meetings
- Informal Meetings
- Meetings of London Students' Section
- COUNCIL
- *Local Centres.*
  - Argentine
  - China
  - Irish
  - Mersey and North Wales (Liverp'l)
    - Mersey and North Wales (Liverp'l) S.S.
  - North-Eastern
    - Tees-Side S.C.
    - North-Eastern S.S.
  - North Midland
    - Sheffield S.C.
    - North Midland S.S.
    - Sheffield S.S.
  - North-Western
    - North-Western S.S.
  - Scottish
    - Dundee S.C.
    - Scottish S.S.
  - South Midland
    - East Midland S.C.
    - South Midland S.S.
  - Western
    - West Wales (Swansea) S.C.
    - Bristol S.S.
  - Hampshire S.C.
  - Northern Ireland S.C.

NOTE:—S.C. denotes a Sub-Centre, and S.S. a Students' Section.

COMMITTEES OF COUNCIL

Examinations
Finance
General Purposes
Library and Museum
Membership
Papers

SPECIAL COMMITTEES

Benevolent Fund
Earthing to Water Mains (Joint)
Electrical Engineers' Ball
Electrical Interference with Broadcasting
Electricity (Supply) Regulations
Faraday Medal and Honorary Membership Advisory
H.T. Conference, Paris, British National Committee
Informal Meetings
International Relations
Local Centres
Meter and Instrument Section
Model General Conditions
Overseas Activities
Patent Law
Scholarships
Science Abstracts
Ship Electrical Equipment Regulations
Transmission Section
Wireless Section
Wiring Regulations

Technical Committees.
Applications and Plant
Electricity in Mines
Electrochemistry and Electrometallurgy
Power Stations and their Equipment
Radiological and Electromedical Apparatus
Telegraphs and Telephones
Traction, including Railways

Overseas Committees.
Ceylon
India (Bombay, Calcutta, Lahore, and Madras)
New South Wales
Queensland
South Australia
Victoria and Tasmania
Western Australia
New Zealand
Transvaal

BODIES ON WHICH THE INSTITUTION IS REPRESENTED

Bristol University
British Cast Iron Research Association
British Electrical and Allied Industries Research Association
British Electrical Development Association, Committee on Rural and Agricultural Electrification
British National Illumination Committee of the International Illumination Commission
British Standards Institution
Building Industries National Council (Advisory Committee on Building Acts and Bye-laws)
City and Guilds of London Institute
Council for the Preservation of Rural England
Electrical Association for Women
Electricity Commission, Conference on Rural Electrification
Engineering Joint Council
Imperial College of Science and Technology, Governing Body
Imperial Minerals Resources Conference, Copper Committee
Institute of Industrial Administration, Examinations Advisory Council
Institute of Metals, Corrosion Research Committee
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Civil Engineers, Earthing to Water Mains Sub-Committee
International Association for Testing Materials
International Electrotechnical Commission, British National Committee
Joint Committee on Materials and their Testing
Joint Fuel Committee
League of Nations Health Organization, Committee on Health and Comfort Conditions in Housing
Leeds Municipal Technical Library Committee
Loughborough Technical College, Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
National Certificates and Diplomas in Electrical Engineering, Joint Committees for
National Committee on Physics (Royal Society)
National Committee on Radio-Telegraphy (Royal Society)
National Physical Laboratory, General Board
National Register of Electrical Installation Contractors
National Smoke Abatement Society
Professional Classes Aid Council
Royal Engineer Board
Science Museum, South Kensington, Advisory Council
Town Planning Institute, Committee on Overhead Transmission Lines
Union of Lancashire and Cheshire Institutes, Panel for Engineering
University College, Nottingham, Electrical Engineering Advisory Committee
War Office Mechanization Board
Women's Engineering Society
World Power Conference, British National Committee

THE INSTITUTION OF ELECTRICAL ENGINEERS

REVENUE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1936.

Dr. EXPENDITURE.

Year ended 31 Dec., 1935. £ s. d.		£ s. d.	£ s. d.
	To MANAGEMENT:—		
	Salaries and Wages	15,882 9 10	
	Staff Provident Scheme	1,450 6 6	
	National Insurance	120 16 7	
	Audit Fee	99 15 0	
	Printing	682 13 9	
	Stationery and Office Requisites	763 0 0	
	Addressing Machine Requisites	45 10 0	
	Postage of Correspondence and Notices	1,035 12 3	
	Telephone	122 6 10	
	Travelling Expenses	302 16 5	
20,775 8 11			20,505 7 2
	,, INSTITUTION BUILDING:—		
	Ground Rent	2,201 0 0	
	Rates	3,158 2 10	
	Heating	668 5 2	
	Lighting and Power	496 17 6	
	Insurance	203 0 1	
	Transferred to Repairs Suspense Account	1,000 0 0	
	New Electrical Heating and Ventilating System	5,732 7 0	
	Household Requisites and Cleaning	605 14 5	
		14,065 7 0	
	Less Rents from Tenants	5,525 0 0	
3,699 5 9			8,540 7 0
357 15 5	,, FURNITURE AND FITTINGS (Repairs and Renewals)		383 1 5
	,, JOURNAL:—		
	Printing	6,926 13 2	
	Postage	2,906 14 5	
	Wrappers and Envelopes	377 13 7	
		10,211 1 2	
	Less Sales and Advertisements	3,644 2 5	
7,267 5 0			6,566 18 9
79 6 4	,, PROCEEDINGS OF THE WIRELESS SECTION (Printing, Postage, etc.: *less* Sales)		70 11 3
594 10 10	,, STUDENTS' QUARTERLY JOURNAL (Editing, Printing, Postage, etc.: *less* Sales)		562 6 11
124 8 6	,, LENDING LIBRARY (Books, Printing, Postage, etc.)		180 12 11
	,, SCIENCE ABSTRACTS:—		
	Abstracting, Editing, Printing, Postage, etc.	5,539 19 6	
	Less Subscriptions, Sales and Advertisements	5,039 1 6	
419 9 0			500 18 0
	Carried Forward		£37,310 3 5

INCOME. Cr.

Year ended 31 Dec., 1935. £ s. d.		£ s. d.	£ s. d.
41,691 1 1	By SUBSCRIPTIONS		43,306 12 8
1,141 7 0	,, ENTRANCE FEES		1,275 15 0
57 12 5	,, LIFE COMPOSITIONS		105 10 0
5,815 4 5	,, DIVIDENDS AND INTEREST		5,924 10 10
180 11 1	,, SALES OF "MODEL GENERAL CONDITIONS"		128 18 10
300 8 7	,, SALES OF "WIRING REGULATIONS"		186 14 0
17 0	,, SALES OF "SHIP WIRING REGULATIONS"		5 0 9
	,, EXAMINATIONS:—		
	Graduateship Examination (Candidates' Fees and Sale of Papers, *less* Examiners' Fees, Printing, etc.)	660 17 10	
	National Certificates and Diplomas (Candidates' and School Authorities' Fees, *less* Assessors' Fees, Stationery, Postage, Travelling Expenses, etc.)	765 6 2	
1,484 9 11			1,426 4 0
	Carried Forward		£52,359 6 1

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

		£ s. d.	£ s. d.
	Brought Forward		37,310 3 5
	To INSTITUTION MEETINGS:—		
	Advance Proofs	293 14 6	
	Reporting	156 19 6	
	Grant to London Students' Section	43 9 1	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	420 8 0	
	Travelling Expenses of Authors of Papers	84 6 11	
	Overseas Meetings	141 17 5	
	Talking Pictures	126 5 0	
1,371 13 11			1,292 0 5
	,, LOCAL CENTRES:—		
	Money Grants (including Travelling Expenses of Authors of Papers)	3,679 12 4	
	Travelling Expenses	686 8 9	
	Faraday Lectures	527 17 0	
	Students' Lectures	112 14 11	
4,813 7 5			5,006 13 0
322 7 5	,, PREMIUMS FOR PAPERS		328 17 9
1,036 10 9	,, SCHOLARSHIPS		1,389 17 10
	,, SPECIAL GRANTS:—		
	British Standards Institution	1,000 0 0	
	Electrical Research Association	1,000 0 0	
	National Illumination Committee	32 0 0	
	International Electrotechnical Commission, Plenary Meeting in 1938 (1st instalment)	350 0 0	
	Paris Conference on High Tension Systems	16 15 9	
	World Power Conference	50 0 0	
	International Association for Testing Materials	26 5 0	
	International Commission on Telephonic Interference	19 13 2	
	Building Industries National Council	50 0 0	
2,340 17 2			2,544 13 11
—	,, BUST OF FARADAY PRESENTED TO AMPÈRE MUSEUM, LYONS		24 0 0
87 9 3	,, ANNUAL DINNER		87 9 2
680 4 8	,, CONVERSAZIONES		691 15 0
166 8 0	,, LEGAL EXPENSES		157 11 0
169 18 0	,, MISCELLANEOUS EXPENSES		135 10 9
44,306 6 4			48,968 12 3
277 12 2	,, AMOUNT TRANSFERRED TO SINKING FUND (Premiums for Redemption of Cost of Building and Lease)	277 12 2	
6,087 13 0	,, **Balance carried to Balance Sheet**	3,113 1 8	
6,365 5 2			3,390 13 10
50,671 11 6			£52,359 6 1

INCOME—*continued.* **Cr.**

		£ s. d.
	Brought Forward	52,359 6 1
50,671 11 6		£52,359 6 1

BALANCE SHEET, 31st DECEMBER, 1936.

Dr. LIABILITIES.

	£	s.	d.	£	s.	d.
To Uninvested Balances of Trust Funds				315	2	4
,, Sundry Creditors				6,165	1	4
,, Subscriptions received in advance				378	4	11
,, Repairs Suspense Account:—						
Balance at 1st January, 1936	4,162	17	4			
Amount set aside in 1936	1,000	0	0			
	5,162	17	4			
Less Expenditure on Repairs in 1936	1,261	19	0			
				3,900	18	4
Carried Forward				£10,759	6	11

ASSETS. Cr.

	£	s.	d.	£	s.	d.
By Institution Building and Lease:—						
Cost	73,028	6	10			
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	10,357	3	3			
				62,671	3	7
,, Sinking Fund (Surrender Values of Policies for Redemption of Cost of Building and Lease)				10,357	3	3
,, Library (exclusive of the Ronalds Library and Faraday Papers, which are held in trust):—						
As per last Balance Sheet	1,911	2	7			
Additions in 1936	259	4	8			
	2,170	7	3			
Less Depreciation (10%)	217	0	9			
				1,953	6	6
,, Thompson Memorial Library (Contribution towards purchase)				1,000	0	0
,, Furniture, Fittings, and Apparatus:—						
As per last Balance Sheet	3,532	16	0			
Less Depreciation (5%)	176	12	10			
				3,356	3	2
,, Sundry Debtors				2,681	12	0
,, Insurance Premiums and Sundry Payments in Advance				1,482	7	11
,, Stock of Paper, Etc., for Publications				618	9	8
,, Investments (at cost):—						
£2,600 Natal Zululand Railways 3% Debenture Stock	2,270	12	0			
£1,500 London, Midland and Scottish Railway 4% Preference Stock	1,513	10	4			
£2,000 Assam Bengal Railways 3% Stock (1931 or after)	1,548	0	6			
£750 Western Australia 4% Stock (1942–62)	730	8	3			
£750 Union of South Africa 4% Stock (1943–63)	742	12	0			
£750 Madras and Southern Mahratta Railway 4% Debenture Stock (1938)	738	15	6			
Carried Forward	£7,543	18	7	£84,120	6	1

BALANCE SHEET—*continued*.

Dr. LIABILITIES—*continued*.

		£ s. d.	£ s. d.
Brought Forward		.. .. ..	10,759 6 11
To Surplus of Assets over Liabilities:—			
Balance at 1st January, 1936		206,704 6 5	
Excess of Income over Expenditure for 1936 brought forward from Revenue Account		3,113 1 8	
		209,817 8 1	
Less Allocation to Supplementary Superannuation Account	£750 0 0		
Depreciation:—			
Library (*per contra*) ..	£217 0 9		
Furniture, Fittings, and Apparatus (*per contra*)	176 12 10		
		1,143 13 7	
			208,673 14 6
			£219,433 1 5

FRANK CRAWTER,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

ASSETS—*continued*. Cr.

	£ s. d.	£ s. d.
Brought Forward	.. ..	84,120 6 1
By Investments (at cost)—*contd.*		
Brought forward	7,543 18 7	
£35 East Indian Railway " B " Annuity (1953) ..	791 5 4	
£1,500 South Australia 4% Stock (1940–60) ..	1,494 10 6	
£6,450 3½% War Stock	6,306 9 0	
£19,375 4% Funding Loan (1960–90)	15,500 0 0	
£8,700 3½% Conversion Stock (1961 or after) ..	6,651 3 3	
£11,970 11s. 4% Consolidated Stock	10,291 6 6	
£1,000 London, Midland and Scottish Railway 5% Preference Stock (1955)	1,020 4 6	
£4,800 North Metropolitan Power Station 5% Guaranteed Debenture Stock (1957)	4,788 11 0	
£2,000 London, Midland and Scottish Railway 5% Redeemable Debenture Stock (1952)	1,982 5 9	
£2,300 East Indian Railway 4½% Irredeemable Debenture Stock	2,019 13 0	
£5,000 Commonwealth of Australia 5% Stock (1945–75)	4,964 17 6	
£2,000 Tynemouth Corporation 5% Stock (1947–57)	2,025 4 0	
£2,500 Stoke-on-Trent Corporation 5% Stock (1948–68)	2,550 6 0	
£3,500 East Indian Railway 3½% Debenture Stock (1937)	2,475 15 6	
£5,000 Brighton Corporation 4¾% Stock (1945–75)	5,050 8 0	
£2,000 New South Wales 5¼% Stock (1947–57) ..	2,013 19 0	
£2,600 Kenya Government 4½% Stock (1950) ..	2,483 4 0	
£3,000 Southern Railway 4% Debenture Stock ..	2,520 5 0	
£2,500 India 4½% Stock (1958–68)	2,329 17 9	
£2,500 Corporation of London 4½% Debenture Stock (1940–85)	2,462 14 0	
£3,000 Birmingham Corporation 4½% Stock (1948–68)	2,906 11 0	
£3,000 London County 4½% Stock (1945–85) ..	2,936 11 0	
£1,000 Bootle Corporation 4¾% Stock (1949–59)	967 12 0	
£10,000 5% Conversion Stock (1944–64)	9,888 5 10	
£2,000 Southampton Corporation 5% Stock (1947–67)	2,027 14 0	
£2,333 London Passenger Transport Board 4½% " A " Stock (1985–2023)	2,110 5 0	
£2,000 Agricultural Mortgage Corporation 5% Debenture Stock (1959–89)	2,080 11 0	
£2,400 Ayr County Council 5% Stock (1947–57)	2,484 4 0	
£2,400 Union of South Africa 5% Stock (1950–70)	2,436 4 0	
£1,000 Nyasaland Government 4½% Guaranteed Stock (1952–72)	1,142 13 0	
£2,500 London Passenger Transport Board 5% " B " Stock (1965–2023)	3,017 1 0	
£5,000 London County 2¾% Consolidated Stock (1960–70)	4,811 2 6	
(*Market value* 31*st December*, 1936, £149,893 5s. 9d.) ..		124,074 12 6
,, Cash in Hands of Local Centres on 30 Sept., 1936	..	1,476 0 5
,, Cash:—		
At Bank	1,007 19 5	
At Banks in Australia and New Zealand	8,499 16 3	
In hands of Secretary	254 6 9	
		9,762 2 5
		£219,433 1 5

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1936, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of The Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of The Institution.

21st April, 1937.

ALLEN, ATTFIELD & CO., *Auditors*,
Chartered Accountants,
24, Martin Lane, Cannon Street, E.C. 4.

SALOMONS SCHOLARSHIP TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,155 14 10	By Investments (at cost):—	
Less Loss on Redemption of £500 Cape of Good Hope 3½% Stock (1929–49) ..	70 13 6	£1,600 13s. 3d. Commonwealth of Australia 3% Stock (1955–58)	1,585 1 4
		£500 Cardiff Corporation 3% Stock (1952–55)	500 0 0
	£2,085 1 4		£2,085 1 4

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1936	100 0 0	By Dividends received in 1936	84 19 5
		,, Contribution from Institution	15 0 7
	£100 0 0		£100 0 0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,000 0 0	By Investment (at cost):—	
		£2,045 Metropolitan Water Board (Staines Reservoirs) 3% Guaranteed Debenture Stock (1922 or after)	1,998 15 0
		,, Balance carried to Balance Sheet*	1 5 0
	£2,000 0 0		£2,000 0 0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1936	100 0 0	By Dividends received in 1936	60 19 3
		,, Interest received in 1936	0 0 6
		,, Contribution from Institution	39 0 3
	£100 0 0		£100 0 0

PAUL SCHOLARSHIP FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,000 0 0	By Investments (at cost):—	
		£625 4% Funding Loan (1960–90)	500 0 0
		£518 3s. 8d. Central Electricity Board 5% Debenture Stock (1950–70)	500 0 0
	£1,000 0 0		£1,000 0 0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1936	50 0 0	By Balance (as per last Account)	22 13 4
,, Balance carried to Balance Sheet*	23 8 3	,, Dividends received in 1936	50 14 11
	£73 8 3		£73 8 3

* Included in the total of £315 2s. 4d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	3,049 16 2	By Investments (at cost):—	
		£1,308 London and North Eastern Railway 4% First Guaranteed Stock	1,744 3 11
		£100 London County 2½% Consolidated Stock (1960–70)	101 8 6
		£250 New South Wales 4% Stock (1942–62)	251 6 0
		£500 3½% War Stock	501 9 3
		£381 15s. 1d. 4% Funding Loan (1960–90)	300 0 0
		£200 3½% Conversion Stock (1961 or after)	151 8 6
	£3,049 16 2		£3,049 16 2

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grants made in 1936	152 0 0	By Balance (as per last Account)	76 18 10
,, Balance carried to Balance Sheet*	29 3 0	,, Dividends received in 1936	103 18 11
		,, Interest received in 1936	0 5 3
	£181 3 0		£181 3 0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,700 0 0	By Investment (at cost):—	
		£2,000 3½% War Stock	1,700 0 0
	£1,700 0 0		£1,700 0 0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grants made in 1936	75 0 0	By Dividends received in 1936	70 0 0
		,, Balance carried to Balance Sheet*	5 0 0
	£75 0 0		£75 0 0

PAGE PRIZE FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	100 19 5	By Investments (at cost):—	
		£50 3½% War Stock	50 19 5
		£51 16s. 4d. Central Electricity Board 5% Debenture Stock (1950–70)	50 0 0
	£100 19 5		£100 19 5

PAGE PRIZE FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Balance carried to Balance Sheet*	10 19 10	By Balance (as per last Account)	6 13 4
		,, Dividends received in 1936	4 6 6
	£10 19 10		£10 19 10

THORROWGOOD SCHOLARSHIP TRUST FUND (Capital).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,000 0 0	By Investment (at cost):—	
		£1,005 Agricultural Mortgage Corporation 5% Debenture Stock (1959–89)	1,000 0 0
	£1,000 0 0		£1,000 0 0

* Included in the total of £315 2s. 4d. shown on the Liabilities side of the Balance Sheet.

THORROWGOOD SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1936	50	0	0	By Balance (as per last Account)	58	2	0
,, Balance carried to Balance Sheet*	58	0	8	,, Dividends received in 1936	49	18	8
	£108	0	8		£108	0	8

SWAN MEMORIAL SCHOLARSHIP FUND (Capital).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last account)	2,968	12	4	By Investments (at cost):—			
				£1,000 Sunderland Corporation 5% Stock (1946–56)	1,116	13	0
				£640 Sunderland Corporation 5% Stock (1950–60)	728	8	0
				£1,135 17s. 9d. 3½% Conversion Stock (1961 or after)	1,123	11	4
	£2,968	12	4		£2,968	12	4

SWAN MEMORIAL SCHOLARSHIP FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1936	120	0	0	By Balance (as per last Account)	22	1	10
,, Balance carried to Balance Sheet*	23	1	8	,, Dividends received in 1936	120	19	10
	£143	1	8		£143	1	8

WILLIAM BEEDIE ESSON SCHOLARSHIP TRUST FUND (Capital).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	3,006	2	6	By Investments (at cost):—			
				£1,500 3½% War Stock	1,603	2	6
				£200 New Zealand 5% Stock (1949) ..	233	0	0
				£250 St. Helen's Corporation 5% Stock (1950–70)	293	15	0
				£250 Sunderland Corporation 5% Stock (1950–60)	293	15	0
				£250 Birmingham Corporation 5% Stock (1946–56)	291	5	0
				£250 Grimsby Corporation 5% Stock (1950–60)	291	5	0
	£3,006	2	6		£3,006	2	6

WILLIAM BEEDIE ESSON SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Balance carried to Balance Sheet*	135	8	10	By Balance (as per last Account)	30	2	6
				,, Dividends received in 1936	105	6	4
	£135	8	10		£135	8	10

SUPPLEMENTARY SUPERANNUATION ACCOUNT.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	1,563	12	10	By Investment (at cost):—			
,, Amount allocated in 1936	750	0	0	£2,214 11s. 7d. 3½% War Stock	2,345	14	1
,, Dividends received in 1936	70	16	4	,, Balance carried to Balance Sheet*	38	15	1
	£2,384	9	2		£2,384	9	2

* Included in the total of £315 2s. 4d. shown on the Liabilities side of the Balance Sheet.

PROCEEDINGS OF THE INSTITUTION

913TH ORDINARY MEETING, 15TH APRIL, 1937

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 8th April, 1937, were taken as read and were confirmed and signed.

A paper by Colonel A. S. Angwin, D.S.O., M.C., and R. A. Mack, Members, entitled "Modern Systems of Multi-Channel Telephony on Cables" (see page 573), was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

914TH ORDINARY MEETING, 22ND APRIL, 1937

Mr. H. T. Young, President, took the chair at 6 p.m.

The minutes of the meeting held on the 15th April, 1937, were taken as read and were confirmed and signed.

Messrs. L. L. Allen and C. L. Lipman were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the Chairman reported that the members whose names appeared on the lists (see vol. 80, page 591), had been duly elected and transferred.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. H. Grimmitt, A. G. Kemsley, and F. Pooley were appointed scrutineers of the ballot for the election of new Members of Council.

Professor J. Chadwick, F.R.S., then delivered the Twenty-Eighth Kelvin Lecture, entitled "The Elementary Particles of Matter" (see page 697).

A vote of thanks to the lecturer, proposed by Lieut.-Col. K. Edgcumbe, and seconded by Prof. C. L. Fortescue, O.B.E., M.A., was carried with acclamation.

65TH ANNUAL GENERAL MEETING, 6TH MAY, 1937

Mr. H. T. Young, President, took the chair at 6 p.m.

The notice convening the meeting was taken as read.

The minutes of the Ordinary Meeting held on the 22nd April, 1937, were also taken as read and were confirmed and signed.

Messrs. I. O. Hockmeyer and A. G. Adley were appointed scrutineers of the ballot for the election and transfer of members, and, at the end of the meeting, the President reported that the members whose names appeared on the list (see vol. 80, page 679) had been duly elected and transferred.

The Premiums (see vol. 80, page 677) awarded by the Council for papers during the session were then announced by the President.

The President next summarized the Annual Report of the Council (see page 792) and moved its adoption. The motion was seconded by **Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng.**

Mr. L. W. Phillips touched upon a number of matters and *inter alia* suggested that more time should be allotted to the Annual General Meeting and also that an Education Section of The Institution be set up.

After **The President** had thanked Mr. Phillips for his suggestions, the motion for the adoption of the Annual Report was put to the meeting and carried unanimously.

Mr. F. W. Crawter (*Hon. Treasurer*), in moving "That the Statement of Accounts and Balance Sheet for the year 1936* as presented be received and adopted," said: "If the members will turn to the right-hand column on page 802, they will see where our income comes from. It will be observed that subscriptions last year brought in more than in the previous year, that entrance fees are up, that life compositions are slightly higher, and that dividends and interest are also a little more than they were in 1935. The amount received from our publications varies from year to year according to whether new editions are issued. In the present instance the amount is slightly lower than a year ago. As I have mentioned on previous occasions, the figures opposite 'Graduateship Examination' and 'National Certificates and Diplomas' do not represent a profit to The Institution. They are simply the amounts received from fees and the sale of papers, less examiners' fees and printing, etc., and they do not include anything for overheads, which come under 'Management.'

"The total receipts on Income account last year were £52 359, which is £1 688 more than in the previous year. On turning to the left-hand column on page 802, it will be seen how that money has been spent. The first item is 'Management,' the cost of which was £20 505 last year as against £20 775 the previous year. The cost of the Institution Building shows a considerable increase, namely from £3 700 to £8 540, due, as mentioned in the Annual Report, to the installation of a completely new system of electrical heating and ventilation throughout the building, which I think everybody will agree is a very marked improvement. The cost of 'Furniture and Fittings' is about the same. The cost of the *Journal* varies from year to year according to the

* See page 802.

number of pages, and it must tend to increase owing to the larger number of copies required as our membership grows; in the present instance the cost is down because a saving has been effected on printing and postage owing to there being a smaller number of pages and to the amount received from sales and advertisements being higher than last year. The cost of the *Wireless Section Proceedings* and of the *Students' Quarterly Journal* is about the same. The cost of the Lending Library is up, which I think is a healthy sign, because it indicates that more advantage is being taken of the Library. The cost of *Science Abstracts*, Institution Meetings, and Local Centres, and the items 'Scholarships,' 'Special Grants,' 'Annual Dinner,' 'Conversaziones,' and 'Legal Expenses,' are much about the same. The net effect is that we transfer £3 113 to the Balance Sheet.

"If members will turn to page 804, they will see in the right-hand column what our Assets are. The cost of the Institution Building, in accordance with our usual practice, is stated at the price we paid for it, and we deduct every year an increasing amount as the surrender value of our policies increases; that is to say, the item of £73 028 will gradually be extinguished as the Sinking Fund grows. 'Sundry Debtors' are £2 681, and our stock of paper is £618. Then comes the list of investments, which cost us £124 074 and were valued on the 31st December last at £149 893. They were revalued, in accordance with our usual practice, last week and were down to £144 254, but that is still 16 per cent over their cost. To the investments we have to add Cash in the hands of the Local Centres £1 476, and Cash at the bank £1 007. Then there is an item 'At banks in Australia and New Zealand, £8 499.' As I explained last year, we cannot transfer that money to our funds here except at very considerable depreciation, so we have deposited the amount in New Zealand at $2\frac{1}{2}$ % and that in Australia at 3 %. That makes our total Assets £219 433. Against that our Liabilities, as shown in the left-hand column, are only £10 759. Adding the amount of £3 113 which we transferred from Revenue Account to the balance brought forward from last year, and making the small adjustment shown in the left-hand column of page 805, a surplus of £208 673 is obtained, which is roughly £2 000 better than last year.

"I cannot claim any personal credit for this result, but I must admit that I feel a certain amount of satisfaction in being able to bring to your notice such very tangible evidence of the abounding vitality of our Institution."

The motion was seconded by **Sir Thomas Purves, O.B.E.,** and, after the Hon. Treasurer had replied to points raised by two members, it was then put to the meeting and carried unanimously.

The President then moved "That the best thanks of The Institution be accorded to the following officers for their valuable services during the past year: (*a*) the Hon. Secretaries of the Local Centres; (*b*) the Local Hon. Secretaries abroad; and (*c*) the Hon. Treasurer, Mr. F. W. Crawter."

The resolution was seconded by **Mr. T. Carter** and was carried with acclamation.

Mr. J. M. Kennedy then moved "That Messrs. Allen, Attfield and Co. be appointed auditors for the year 1937–38." The motion was seconded by **Mr. H. Bishop** and was carried unanimously.

The meeting then terminated.

915TH ORDINARY MEETING, 6TH MAY, 1937

Mr. H. T. Young, President, took the chair at 6.45 p.m., immediately after the conclusion of the Annual General Meeting.

The President announced that, during the month of April, 279 donations and subscriptions to the Benevolent Fund had been received, amounting to £182. A vote of thanks was accorded to the donors.

Mr. R. S. Whipple, Member, then delivered the Thirteenth Faraday Lecture, entitled "Electricity in the Hospital."

A vote of thanks to the lecturer, moved by the President, was carried with acclamation.

THE BENEVOLENT FUND

39TH ANNUAL GENERAL MEETING, 6TH MAY, 1937

Mr. H. T. Young, President, took the chair at 5.30 p.m.

The notice convening the meeting was taken as read. The minutes of the 38th Annual General Meeting held on the 7th May, 1936, were also taken as read and were confirmed and signed.

The Report of the Committee of Management (see page 811) and the Statement of Accounts for the year 1936 (see page 812) were presented and, on the motion of the Chairman, seconded by Mr. W. C. P. Tapper, were unanimously adopted.

On the motion of the Chairman it was resolved that Mr. J. Attfield, F.C.A., be appointed Honorary Auditor for the year 1937.

The Chairman reported the constitution of the Committee of Management for the year 1936–37 which had been appointed by the Council (see vol. 80, page 109).

The meeting then terminated.

REPORT OF THE COMMITTEE OF MANAGEMENT OF THE BENEVOLENT FUND FOR 1936

Capital

The Capital Account stood on the 31st December, 1936, at £23 863 2s. 2d., which is invested.

Receipts

The Income for 1936 from dividends, interest, and annual subscriptions, was as follows:—

	£	s.	d.
Dividends and Interest ..	1 057	16	1
2 033 Annual Subscriptions ..	1 066	19	6
	£2 124	15	7

In addition to the foregoing, the Fund benefited during the year by the following donations:—

Donations

	£	s.	d.
Mersey and North Wales (Liverpool) Centre, Golf Tournament ..	170	0	0
Association of Lancashire and Cheshire Electricity Undertakings ..	105	0	0
North-Western Centre, Golf Tournament ..	95	0	0
South Midland Electrical Engineers' Ball ..	65	0	0
British Electrical Development Association: donations from proceeds of Carnivals			
At Newcastle-on-Tyne ..	30	0	0
At Glasgow ..	7	0	0
"The Twenty-Five Club" ..	26	5	0
Western Centre and West Wales Sub-Centre	25	0	2
Incorporated Municipal Electrical Association ..	10	10	0
Incorporated Municipal Electrical Association, Golf Tournament ..	12	8	6
North-Western Centre, Manchester Engineers' Ball ..	15	15	0
North Midland Centre, collections at meetings ..	13	2	6
National Register of Electrical Installation Contractors ..	10	10	0
Overhead Lines Association, portion of balance of funds ..	10	0	0
North Wales Electrical Communications Engineers, surplus from Annual Dinner	8	16	4
South Midlands Students' Section Ball ..	6	6	0
Henley's Telegraph Works Co., Ltd. ..	25	0	0
General Electric Co., Ltd. ..	10	10	0
Messrs. Kennedy and Donkin ..	10	10	0
Messrs. Merz and McLellan ..	10	10	0
Lord Hirst of Witton ..	31	10	0
E. A. Watson ..	31	10	0
H. Marryat ..	23	2	0
G. W. Smart ..	10	10	0
S. S. Moore Ede ..	10	0	0
J. D. Knight ..	6	0	0
V. E. Faning ..	5	5	0
F. C. Raphael ..	5	0	0
Anonymous ..	5	0	0
L. C. F. Bellamy ..	5	0	0
J. M. Donaldson ..	5	0	0
J. M. Kennedy ..	5	0	0
R. G. Kilburne ..	5	0	0
H. E. Morrow ..	5	0	0
G. H. Nisbett ..	5	0	0
K. A. Scott-Moncrieff ..	5	0	0
E. A. Short ..	5	0	0
F. C. Williams ..	5	0	0
and 3 129 donations of under £5 ..	1 133	11	0
	£1 973	16	6

Donors and Subscribers

Lists of the names of donors and subscribers are issued to members of The Institution annually.

The Committee of Management desire to tender their cordial thanks to the donors and subscribers and to intimate that, apart from donations, the Committee will be grateful for annual subscriptions of any amount, as the Committee are anxious that the Capital Account should be steadily augmented, so as to strengthen the financial position of the Fund.

Grants

Applications for assistance were made by or on behalf of 74 persons during 1936, and the Committee, after due consideration, made grants in all the cases except one. In assisting these persons the Fund also provided for the necessities of 86 dependants. In 1935, 61 applications were received and grants were made in every case.

The total amount of the grants in 1936 was £3 720 3s. 3d., which compares with £2 987 0s. 2d. in 1935.

Electrical Engineers' Ball

The annual Electrical Engineers' Ball, held on the 14th February, 1936, realized a surplus of £230 1s. 5d., which was handed over to the Fund.

The Committee desire to record their warm appreciation of the services rendered by the late Mr. A. M. Sillar in connection with the Electrical Engineers' Ball from 1904 to 1936, during which period he was a valuable member of the Ball Committee and latterly their Chairman. Contributors will be gratified to learn that during those years donations of amounts aggregating £2 169 were made to the Benevolent Fund from that source.

Wilde Fund

The Capital Account stood on the 31st December, 1936, at £3 049 16s. 2d., all of which is invested and brings in an annual income of about £104 17s.

The balance standing to the credit of the Income Account (from which, under the Trust Deed, only full Members and their dependants can benefit) on the same date was £29 3s.

Grants amounting to £152 were made from this Fund during the year.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1936.

Dr. EXPENDITURE.

Year ended 31 Dec., 1935. £ s. d.		£ s. d.
2,987 0 2	To Grants	3,720 3 3
26 1 1	,, Printing, Stationery, Postage, etc.	40 5 7
1,098 15 7	,, Unexpended Balance carried to Balance Sheet ..	568 4 8
£4,111 16 10		£4,328 13 6

INCOME. **Cr.**

Year ended 31 Dec., 1935. £ s. d.		£ s. d.	£ s. d.
1,038 11 6	By Dividends and Interest		1,057 16 1
244 2 6	,, London Electrical Engineers' Ball		230 1 5
	,, Donations of £5 and over:—		
	Mersey and North Wales (Liverpool) Centre Golf Tournament	170 0 0	
	North - Western Centre Golf Tournament	95 0 0	
	Incorporated Municipal Electrical Association, Golf Tournament	12 8 6	
	South Midland Electrical Engineers' Ball	65 0 0	
	North-Western Centre, Manchester Engineers' Ball ..	15 15 0	
	British Electrical Development Association, Carnivals at Newcastle-on-Tyne and Glasgow ..	37 0 0	
	The Association of Lancashire and Cheshire Electricity Undertakings	105 0 0	
	Other donations	340 2 0	
729 2 8			840 5 6
1,109 5 2	,, Donations under £5		1,133 11 0
990 15 0	,, Annual Subscriptions		1,066 19 6
£4,111 16 10			£4,328 13 6

BALANCE SHEET, 31st DECEMBER, 1936.

Dr. LIABILITIES.

		£	s.	d.
To Capital Account:—				
As per last Balance Sheet		23,863	2	2
,, Income and Expenditure Account:—				
As per last Balance Sheet	£2,940 7 6			
Unexpended Balance in 1936	568 4 8			
		3,508	12	2
,, Grants authorized but not yet disbursed		67	0	0
,, Sundry Creditors		7	16	0
,, Subscriptions and Donations received in advance		7	4	0
		£27,453	14	4

ASSETS. Cr.

		£	s.	d.
By Investments (Capital), at cost:—				
£961 7s. 7d. Cape of Good Hope 3% Stock (1933–43)		950	0	0
£420 London and North Eastern Railway 4% First Preference Stock		503	18	3
£450 London, Midland and Scottish Railway 4% Debenture Stock		551	0	9
£750 East Indian Railway 3½% Debenture Stock		737	18	0
£300 London, Midland and Scottish Railway 4% Guaranteed Stock		333	11	6
£500 New Zealand 3½% Stock (1940)		486	18	6
£500 Canada 3½% Stock (1930–50)		478	16	0
£5,800 3½% War Stock		5,783	6	1
£350 New South Wales 4% Stock (1942–62)		336	18	6
£2,580 4% Funding Stock (1960–90)		2,123	15	6
£3,295 3½% Conversion Stock (1961)		2,512	11	10
£450 Commonwealth of Australia 5% Stock (1945–75)		438	16	0
£450 Tynemouth Corporation 5% Stock (1947–57)		457	7	3
£950 Agricultural Mortgage Corporation 5% Debenture Stock (1959–89)		988	5	6
£1,000 Southern Railway 5% Redeemable Guaranteed Preference Stock (1957)		1,028	7	0
£1,000 Southern Railway 5% Guaranteed Preference Stock		1,000	3	0
£1,000 Hastings Corporation 5% Stock (1947–67)		980	2	0
£800 London Passenger Transport Board 5% "A" Stock (1985–2023)		808	2	6
£700 Ayr County Council 5% Stock (1947–57)		733	7	0
£1,000 Commonwealth of Australia 4% Stock (1955–70)		1,012	13	0
£900 South Essex Waterworks Co. Perpetual Debenture 4% Stock		1,014	4	6
£650 London County Council 2¾% Consolidated Stock (1960–70)		602	19	6
		£23,863	2	2
(*Market value 31st December*, 1936, *£27,324 10s. 4d.*)				
,, Investments (Income) at cost:—				
£1,050 Newcastle and Gateshead Water Co. 5% Consolidated Preference Stock	£1,513 14 6			
£500 London County Council 2¾% Consolidated Stock (1960–70)	487 11 0			
£1,000 3% Funding Stock (1959–69)	1,033 5 6			
		3,034	11	0
(*Market value 31st December*, 1936, *£2,985 0s. 0d.*)				
,, Sundry Debtors		10	10	0
,, Cash:—				
At Bank	539 7 9			
In hand	6 3 5			
		545	11	2
		£27,453	14	4

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Banks.

21st April, 1937.

JAS. ATTFIELD, F.C.A.,
Honorary Auditor.

INSTITUTION NOTES

INDEX TO JOURNAL

Any member who proposes to bind the current volume of the *Journal* and would like to have an extra copy of the Index, for filing apart from the bound copy of the *Journal*, can obtain an additional copy on application to the Secretary.

LIST OF MEMBERS

Copies of the new List of Members corrected to the 1st September, 1937, are now available. Any member wishing to receive a copy should apply to the Secretary of The Institution.

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of The Institution and its Local Centres, and, when occasion arises, to put them in touch with other members.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

SENIOR-SCHOOL CHRISTMAS LECTURES IN ENGINEERING

Arrangements have been made by the Engineering Public Relations Committee, consisting of representatives of the leading engineering Institutions, for two Christmas Lectures for young people to be delivered this season by Prof. C. E. Inglis, C.B.E., M.A., LL.D., F.R.S., on the subject of "Building Big Bridges." These two lectures will be delivered in the I.E.E. Lecture Theatre on Friday, 7th January, and Monday, 10th January, 1938, at 3 p.m. It is the intention of the Committee that the audience at these lectures should be limited as far as possible to boys between the ages of 15 and 20 years, admission being by ticket only, obtainable in advance. Members of The Institution of Electrical Engineers who require tickets should apply for them as soon as possible to the Secretary, I.E.E., Savoy Place, London, W.C.2.

TRANSFERS

The following transfers were effected by the Council at their meeting held on the 2nd December, 1937:—

Associate to Graduate.

Constable, Leslie Stuart.

Student to Graduate.

Allan, Arthur Quinton.
Ananthanarayanan, Chittur Seshaier.
Anwar-Ali, Chaudhary.
Armstrong, Gordon, M.Sc.
Atkinson, Leslie Frederick, B.Sc. (Eng.).
Ball, Herbert.
Bennell, Frank Tasman.
Bett, Neil Alexander, B.Sc. (Eng.).
Bruty, Alfred Owen.
Cochrane, Thomas Richard H.
Dorey, Bernard Edgar.
Field, Dennis Cromwell.
Flannery, Sidney Thomas.
Follenfant, John Lindsay.
Ford, Wilbraham Randle.
Garner, Gerald Bernard, B.Sc.(Eng.).
Goff, Harford Stanley H.
Goldstaub, Heinz Herbert.
Green, Gilbert Harold, B.Sc.Tech.
Hawke, Arthur Edgar, B.Sc.(Eng.).
Hunter, Tom de Rohan H.
Jarman, Frank Edgar.
Lay, William.
Lovegrove, William George.
Marr, Davis, B.Sc.(Eng.).
Metcalfe, John, B.Sc.
Millar, John Boyer.
Miller, Arthur.
Monahan, Thomas Francis, B.Sc.
Nasif, Mohammed Abd el L., B.Sc.
Nathan, Alan John.
Nicholson, Henry, B.Sc.
Norton, Charles James.
Parsons, Louis William, B.Sc.(Eng.).
Phillips, James Huntley, B.Sc.
Preston, Lindley Lloyd, B.Sc.Tech.
Roes, Robert Carey.
Saker, Dudley Carlyle, B.Sc.
Salt, Thomas Charles F., B.Sc.
Shepherd, Ronald Bradley.
Smith, Jonathan William.
Stockdale. Leonard Alfred, B.Sc.(Eng.).
Swift, Brian Mastin.
Thornton, John Godfrey, B.Sc.Tech.
Walker, John Egan.
Walrond, Herbert.
Welbourn, Donald Burkewood.
Wood, Harald Isbister, B.Sc.

OBITUARY NOTICES

ROBERT LAWFORD ACLAND died on the 30th April, 1937, at the age of 64. He entered upon his practical training in 1891 as a pupil in the locomotive shops of the Birmingham Central Tramways Co. and also attended classes at the Midland Institute, Birmingham. In 1892 he was placed in charge of the electrical department of his firm and was responsible for working the accumulator traction line on the Bristol Road, Birmingham, as well as for the erection of power and lighting plants. His next position, to which he was appointed in 1894, was that of engineer in charge of the outside work of Messrs. Ellis and Ward, Midland agents for the Anglo-American Brush Co. He left this firm in 1896 to join the Birmingham Electric Supply Co. as an assistant engineer, devoting his attention chiefly to the company's d.c. substations.

After a year with Messrs. Belshaw and Co. he went in 1900 to Chesterfield on his appointment as borough electrical and tramways engineer, a position which he held for some years. He was responsible for the design and erection of all the buildings, plant, and equipment, for the electricity and tramway systems at Chesterfield, and subsequently for their organization and operation. During the War he took charge of the power supplies to several important munitions factories, and organized and commanded the Royal Army Service Corps Volunteers for the County of Derby.

The later years of his career were devoted to sales and publicity work for a number of electrical concerns, including Agricultural and General Engineers, Ltd., Sir W. G. Armstrong Whitworth and Co., Ltd., and the London Electric Wire Co. and Smiths, Ltd. In 1929 he joined the staff of the British Electrical Development Association and went to India in connection with a publicity scheme for the supply undertakings under the control of the British Indian Electric Committee. On his return to this country he was employed by the Association on work concerning the development of trolley-buses and other types of electric vehicles. He was also assistant secretary of the Electric Vehicle Committee of Great Britain. He was elected an Associate Member of The Institution in 1904, and a Member in 1907.

ARTHUR THOMAS ARNALL, B.Sc., who was born on the 6th January, 1884, and died on the 4th August, 1937, was educated at St. George's School, Birmingham. Later, in 1910, he obtained the B.Sc. degree of London University by private study. From 1900 to 1903 he served as a pupil under Mr. Alfred Dickinson, consulting engineer; and then for 2 years was assistant engineer on Mr. Dickinson's staff, being engaged in the design of electric tramway systems. From 1905 to 1908 he was employed by Messrs. Dick, Kerr and Co. as an assistant engineer on the construction of electric tramways in London and Birmingham. From 1910 to 1921 he was engaged by Mr. Alfred Dickinson and Messrs. Tata Sons, Ltd., on the design and construction of the Tata hydro-electric power scheme, and subsequently he reported on various hydro-electric projects in India and Ireland. In 1926 he was appointed an executive engineer in the electricity branch of the Public Works Department of the Punjab Government, being promoted to superintending engineer in 1932, and to deputy chief engineer in 1933. He joined The Institution as an Associate Member in 1910 and was elected a Member in 1934.

FRANK BOULTON ASPINALL, who died on the 1st March, 1937, at the age of 72, was an old Finsbury man, training under the late Dr. Silvanus Thompson from 1884 to 1886. After leaving Finsbury, he spent a short time on experimental electro-plating processes. In 1887 he joined Messrs. Laing, Wharton and Down, being engaged on erection work, and was for some time in charge of the central station at Waterford. In 1889, when the power-station department of that firm was taken over by the B.T.H. Co., he joined the latter company.

His long connection with the City of London Electric Lighting Co. really began about that time, as he acted for the B.T.H. Co. as their resident engineer during the erection of the pioneer station of the City Company at Wool Quay, Thames-street, London, and on its completion became superintendent of the station. In 1897, when Wool Quay was closed down, after the new Bankside station had been put into commission, he was appointed superintendent of general distribution, being in charge of all transformer substations and of the public lighting of the City, which position he retained until his retirement in 1932.

He became an Associate of The Institution in 1891, and was elected a Member in 1898. In 1902 he read a paper before The Institution on "Electric Shocks," which was probably the first attempt to arrive at some conclusion on the effect of electric shocks on persons of different constitutions. His chief hobby was dog breeding. He was beloved by all his colleagues, especially the men under his supervision, many of whom have to thank him for anonymous assistance in times of financial stress. His cheery countenance, dry wit, and readiness to assist the under-dog, will be greatly missed by all who knew him.

C. G. C.
E. H.

MORTON BEALES, who died on the 10th December, 1936, at the age of 65, was born in Cambridgeshire, where his ancestors had resided for many generations. He was educated at Cranleigh School, and received his technical training at the Finsbury Technical College. After leaving college he entered Messrs. Ferranti's works at Charterhouse-square as an apprentice, and for some time acted as a junior assistant to Dr. S. Z. de Ferranti in some of that pioneer's experiments. Later he was

attached to the switchgear department of Messrs. Ferranti, helping in the development and on the commercial side of the cellular (slate) type of switchgear. He left that firm in 1900 and joined Messrs. J. G. White and Co. as commercial engineer, at the time when Messrs. White were negotiating for the electrification of the London tramways system, which contract they ultimately secured. In 1902 he obtained an appointment with the British Westinghouse Co. and was engaged in the management side until 1905, when he was appointed by Messrs. Bruce Peebles to be general manager. In 1908 he joined in partnership with Mr. M. M. Gillespie, and continued to be actively interested in the firm of Messrs. Gillespie and Beales until his death. He was a man of high ideals, with a keen sense of duty, and by his friendly, genial character he gained many life-long friends. He joined The Institution as a Member in 1905.
M. M. G.

HARRY COLLINGS BISHOP, who died on the 3rd September, 1937, was born in 1868 and was educated at Bristol Grammar School, where he also acted for some time as electrical demonstrator before going to America in 1888. There he was employed by Messrs. Almand and Phillips, of Seattle, and later by the United Edison Manufacturing Co. In 1891 he became superintendent of the engineering and electrical department of the North-West Electrical Engineering Co., at Portland. Returning to England in 1894 he was engaged for 2 years as a charge engineer at the Bristol Electricity Works, and was then appointed chief engineer and manager to the electrical undertaking of the Leyton Urban District Council. Resigning in 1899, he went as consulting engineer and tramways manager to the Wigan Corporation, where he designed and supervised the construction of the electric lighting system and was also responsible for all the electrical engineering work in connection with the Corporation Tramways.

He was appointed borough electrical and tramways engineer of Newport, Mon., in August, 1902, when the Corporation electrified its tramway system. He left in March, 1912, and then commenced in private practice in Cardiff as an electrical contractor. War came along, and he joined up in 1914. He was commissioned in the 5th Welch Regiment as a subaltern to the writer of this notice, but he subsequently transferred to the Army Service Corps and was stationed for the whole of the War at Aldershot. On demobilization he took up speciality farming in Berkshire, and withdrew from active interest in the electrical industry. He was elected a Member of The Institution in 1903. S. B. H.

JAMES CONNER was born in Glasgow in 1858 and was educated at Ayr Academy and the Andersonian College. He served his apprenticeship at the locomotive shops of the Caledonian Railway and then joined the Hyde Park Locomotive Works at Springburn. In 1885 he went to the Britannia Engineering Co. of Kilmarnock as a locomotive designer. This works was later acquired by Messrs. Dick, Kerr and Co., with which name that of James Conner is so closely associated. In 1900 he was manager of the Kilmarnock works, and in 1901 was moved to Preston to take charge of the new works there. He remained in charge of those works until 1920, when he took up consulting work and continued in harness until his death. He was elected a Member of The Institution in 1912.

Such, in brief, was his career in engineering, but James Conner stood for something more than that. He took no credit for the large amount of inventive design work which he carried out, although he was in the forefront of the application of steam to tramways, in the use of large gas engines in industry, and in the production of electric tramway and railway material in this country. His management of the Preston works of Messrs. Dick, Kerr and Co. coincided with the rise of that firm in the electric tramway and railway world, and he bore the responsibility of converting that works into an armament factory in the first year of the War.

In character, he was both a realist and an idealist, proceeding on broad straight lines, always looking for what was manly and kind, and he possessed an integrity that could be felt. W. E. H.

HARRY AUGUSTUS COUVES was born at Gravesend on the 28th February, 1876, and died on the 25th March, 1937. He served an apprenticeship with Messrs. John Stewart and Co., marine engineers and shipbuilders, at Blackwall, and received his electrical training with Messrs. Siemens Brothers and Co., at Woolwich. Subsequently he joined the staff of Messrs. Merz and McLellan, consulting engineers, and in 1901 took up an appointment in their office at Newcastle-upon-Tyne.

In 1906 he became power engineer of the North-Eastern Electric Supply Co. (then known as the Newcastle-upon-Tyne Electric Supply Co.), which was in those days concentrating on the development of supplies to shipyards, engineering works, collieries, and factories, in the Tyneside area. The success of his efforts is reflected in the fact that, by the time of the outbreak of the War, the connections in the area operated by the company had increased nearly fourfold. During the period of hostilities there were urgent demands upon the company for new power supplies in connection with the manufacture of munitions, but his tenacity enabled him to surmount the difficulties with which he was confronted.

As a result of a post-war change in the company's internal organization, he became head of the newly-formed power and construction department, and his duties, besides embracing responsibility for all industrial supplies, included matters affecting power-station and system extensions throughout an area of supply which, by then, covered the greater part of Northumberland, Durham, and North Yorkshire. He was appointed general manager in 1926, and was elected a director in 1934. At the end of the latter year he became the chief executive official, consequent upon Mr. R. P. Sloan's retirement from the managing directorship. He was also a director of Messrs. Kelvin, Bottomley, and Baird, and of the Thermal Syndicate, and was a member of the National Consultative Committee of the Central Electricity Board, and chairman of the North-East England District Consultative Technical Committee of the Board.

Mr. Couves was a man of charm, and inspired a deep affection in all who came in close contact with him. He was of a retiring disposition but was a born negotiator,

and could always appreciate the other point of view; his judgment was sound and his decisions firm. He never lacked courage, enterprise, or resourcefulness, but exercised the right amount of prudence to avoid rashness. He also possessed a sense of subtle humour. He served his company well, and spared himself no effort in the advancement and expansion of the electrical industry generally.

He was elected a Member of The Institution in 1911.

H. S.

WILLIAM CROSS, who died at Ashtead, Surrey, on the 16th October, 1937, was born at Bridgwater, Somerset, on the 17th November, 1855. He received his preliminary training in engineering at the works of Messrs. William Pope and Sons, Bristol, and afterwards served his apprenticeship with Messrs. Fox and Walker, locomotive engine builders, Bristol. During this period he was an evening student at the Merchant Venturers' College and obtained a Royal Scholarship tenable at the Royal School of Mines, London. There he passed the honours examination in metallurgy, held by the Science and Art Department.

After leaving the Royal School of Mines he was engaged on electrical and chemical research work. During that period he was an evening student at the Finsbury Technical College. He afterwards entered the service of a civil engineer and was engaged on bridge work. Being, however, particularly interested in invention, he left that work to become the principal technical assistant of Sir William Lloyd Wise, consulting engineer and chartered patent agent. Subsequently, in conjunction with some of his colleagues, he took over the practice of Sir William upon the latter's retirement from the profession, and became senior partner in the firm of Lloyd Wise and Co., of Lincoln's Inn. He was elected a Member of The Institution in 1913. W. J. C.

JAMES DOUGLAS DALLAS died on the 26th November, 1936, in his 73rd year. The second son of the late Mr. A. G. Dallas, formerly governor of Rupert's Land, he was educated at University College, London. His earlier professional career was pursued with the Edison General Electric Co., the Thomson-Houston Co. of America, and the India Rubber, Gutta-Percha, and Telegraph Works Co.; and in January, 1895, he began his long association with the County of London Electric Supply Co. (then known as the County of London and Brush Provincial Electric Lighting Co.) which lasted for 38 years. As mains superintendent he connected the first consumer to the company's system, and when he retired in December, 1933, the number of consumers had grown to 150 000. As chief mains engineer he was directly responsible for 4 497 miles of transmission and distribution mains. His knowledge and experience, which were unrivalled, and his foresight were of inestimable value throughout the increase in the company's activities. He was a staunch supporter of the "draw-in" system for the Metropolis and the adjacent areas. He was also one of the pioneers in the introduction of the 11-kV system in 1911, and later the 33-kV system in 1924.

On his retirement his colleagues, assistants, and the employees of the company, presented to him a silver casket containing a roll of vellum bearing 1 800 signatures. He was also presented with a cheque for £147 which represented the balance of the amount subscribed, and at his request this amount was passed on to benevolent associations.

Distinguished as was his professional career, however, he will best be remembered by all those who knew him as a man of infinite courtesy and kindliness. His natural charm was but one of the many attributes which so endeared him to his colleagues, whilst there are many who can bear witness to his generosity and the practical sympathy which was ever at the disposal of all those in need of help or advice.

He joined The Institution as an Associate in 1886, became an Associate Member in 1899, and was elected a Member in 1913. H. C. W.

GEORGE DANIA was born on the 2nd May, 1860, and died on the 30th October, 1937. Between 1873 and 1876 he studied at the Holly Mount College, Bury, and then spent 2 years as a pupil in his father's works at Rochdale. He continued his practical training with Messrs. I. and W. McNaught, of the same town, remaining with them until 1881, when he went to London as a fitter in the employ of the India Rubber, Gutta Percha, and Telegraph Works Co. The following year he joined Mr. I. H. Ladd, of London, as a draughtsman in connection with dynamo and arc-lamp design. From 1884 to 1888 he was employed by various firms in Manchester on the design and erection of machine tools, ultimately becoming an inspecting engineer in charge of electrical work with Messrs. Livesey, Son, and Henderson. He remained with this firm until 1898, and was subsequently for many years in business on his own account as a consulting and inspecting electrical engineer. Among other work which he undertook was the inspection and testing of telegraph and telephone instruments and switchgear for several railways in South America. He was also inspecting engineer for a number of important electric lighting and traction undertakings abroad. Elected an Associate Member of The Institution in 1909, he became a Member in 1926.

AUGUSTINE DAVY, managing director of the Weston Electrical Instrument Co., died on the 18th March, 1937, in his 63rd year. He received his technical education at Finsbury Technical College, and part of his early life was spent as a marine engineer. He then went to America, where from 1900 to 1903 he designed and erected the electric power plant of the Staten Island Electric Light and Power Co. In 1903 he obtained an appointment at the head office of the Weston Electrical Instrument Co., Newark, U.S.A. A year later he was appointed chief engineer and manager of the London branch, and for 33 years he was in charge of the activities of the British company. During the War he served his country in a technical advisory capacity. He was elected a Member of The Institution in 1912.

FREDERICK JONATHAN DOWN was born in 1855 and died on the 17th October, 1937, at the age of 82. He was educated at Sandycroft College and was trained as an engineer at the works of Messrs. A. and W. Smith, Glasgow. He was for some time in the works of Sir C. Tennant and Partner at Hebburn-on-Tyne and subsequently with the Blaydon Manure and

Alkali Co. In 1883 he became a partner in the firm of Messrs. Laing, Wharton, and Down, who shortly afterwards were appointed agents for the Thomson-Houston Co. of America. In 1901 he was called in by the City and South London Railway Co. in connection with the installation of electric lifts. He made a special study of vibration and noise problems, and also acted in a consulting capacity to several fire insurance companies in connection with fire losses. He was elected an Associate of The Institution in 1886 and a Member in 1889.

LENNARD MELVILLE EVANS, who was born on the 28th February, 1884, and died on the 26th March, 1937, received his technical education in evening classes at Chester Technical School and at Wolverhampton Technical College. He served his apprenticeship with the Electric Construction Co., Wolverhampton, and, after considerable experience with the company, left to become assistant engineer in Lagos. In 1911 he was appointed manager of the electrical department of Huttenbachs, Ltd., Penang, eventually becoming a director, and in that position was responsible for the whole of his firm's electrical activities, including a large number of lighting plants both in the Federated and Unfederated Malay States and in the Straits Settlements. He had a very large circle of friends and was an enthusiastic member of the Engineering Association of Malaya, of which he was one of the original members. He joined The Institution as an Associate Member in 1921, and became a Member in 1935. T. R.

EDWARD GRAHAM FLEMING, who died on the 18th January, 1937, at the age of 65, was educated at Dulwich College and at the Central Technical College, South Kensington. He joined Messrs. Siemens Brothers and Co., Woolwich, in 1893, and in the following year took part in three "Faraday" expeditions. He served with the London Scottish in the Boer War and was invalided out of the Army with enteric fever. In 1901 he was appointed manager in Australia for Messrs. Siemens Brothers, and returned to England in 1909 to take charge of the export department of Siemens Brothers Dynamo Works, Ltd. On the formation of the English Electric Co. he went to them as their assistant export manager, and stayed with them until the end of 1930, when he rejoined Messrs. Siemens Brothers and Co. at Woolwich. He joined The Institution as a Student in 1893, and was elected an Associate in 1896, an Associate Member in 1902, and a Member in 1913.

Apart from his profession, he had many interests, and, in particular, devoted much of his leisure time to the Toc H movement. He will be remembered by all who came in contact with him for his natural charm of manner, and for his genuine sympathy with his fellow men and constant regard for their welfare. H. T. R.

SURENDRA NATH GHOSH, who died on the 17th July, 1936, was born in Benares in September, 1885, and was educated at the Central Hindu College, Benares. He came to this country in 1905 and took the evening course in electrical engineering at the Manchester School of Technology. At the same time he served his apprenticeship with the British Westinghouse Electric and Manufacturing Co. He was for a short time on the staff of the company in their testing department and in the power house. He then returned to India and was from 1912 to 1914 lecturer and demonstrator in electrical engineering at the Civil Engineering College, Sibpore, Calcutta. In May, 1914, he was appointed chief electrical engineer to the Tata Iron and Steel Co., Jamshedpur, and held that position for many years. During the War the works were converted for munition work, and, owing to the difficulty in obtaining machinery parts, he arranged for many essential parts to be manufactured in the works. He served on various technical committees and also as a magistrate. He was elected a Student of The Institution in 1908, an Associate in 1911, an Associate Member in 1912, and a Member in 1919.

JOHN OWEN GIRDLESTONE was born on the 10th January, 1861, and died on the 17th February, 1937. In 1874 he was apprenticed for a period of 5 years to Messrs. Simpson and Co., Grosvenor-road, London, and on leaving there went for 1 year to Messrs. George Wailes and Co. He then served as a sea-going engineer officer for 2 years with the Brazil and River Plate Steam Navigation Co. Subsequently he was for a short time with Messrs. Crompton and Co. and whilst with that firm was responsible in 1882 for designing one of the earliest hot-wire voltmeters. For a period of 6 years he was manager of the engineering department of Messrs. Latimer Clark, Muirhead, and Co. He then joined Messrs. Verity and superintended the construction of several large installations, including, among others, the original installation at the Savoy Hotel and that at the New Palace Theatre, London.

In October, 1890, he started in business with a partner as Messrs. Girdlestone and Co., electrical engineers and contractors. In 1896, with others, he formed the Westminster Engineering Co., of which company he was appointed managing director. In 1887, in collaboration with the late Mr. F. E. Anderson, he competed for and won the 100-guineas prize offered by "Industries" for the best design of electric motor. He was the joint inventor and patentee of the "Westminster" arc lamp with which at one time the Central London Railway was lighted. He was elected an Associate of The Institution in 1890, an Associate Member in 1903, and a Member in 1906.

WILLIAM GUY-PELL died at Sunningdale on the 22nd October, 1937. Born at Hartlepool in 1860, he was educated at Bristol Grammar School and the College of Physical Science, Newcastle-on-Tyne. After going through a course of training as a mining engineer at the Hepburn Colliery, Durham, and serving a pupilage from 1876 to 1881 in the marine-engine shop and drawing office of Messrs. Thomas Richardson and Sons, mechanical engineers, of Hartlepool, he was employed by Messrs. Wynne and Co., civil engineers, of London.

In 1882 he commenced a happy 15 years' service with the Brush Electrical Engineering Co., Ltd., then the Anglo-American Brush Electric Light Co., first as assistant manager of their dynamo factory in Borough Road, London, and then as manager of their Scottish branch. In 1892 he was appointed superintending engineer to the company, and was in charge of the construction of electricity supply works at many places,

including Huddersfield, Henley, Bath, Worcester, Dover, Leicester, Lancaster, Coatbridge, and Wandsworth.

In May, 1897, he joined in partnership with the late Mr. F. M. T. Lange and they acquired the contracting and agency departments of Messrs. Paterson and Cooper, which they carried on at Westminster under the title of Geipel and Lange. The firm were appointed southern agents for Messrs. Richardsons Westgarth, of Hartlepool, who held the concession in this country of Messrs. Brown, Boveri. A number of contracts were executed for the electrical driving of works on the 3-phase system, then almost untried in this country. The business was formed into a private company under the name of William Geipel, Ltd., in 1927, and he was chairman until his death.

He made many inventions, including a widely known steam trap, and was the author of numerous papers on electrical subjects, amongst which may be mentioned a paper on "Electric Power and its Application on the Three-Phase system to the Bristol Waggon and Carriage Works," which was read before the British Association in 1898. Elected an Associate of The Institution in 1884, he became a Member in 1889.

Brigadier-General Sir HENRY CAPEL LOFFT HOLDEN, K.C.B., F.R.S., died on the 30th March, 1937. Born in 1856, he was educated at Queen Elizabeth's School, Ipswich, and at the Royal Military Academy, Woolwich. He joined the Royal Artillery in 1875 and saw service in India. In 1881 he took up technical work, being made a captain inspector at Woolwich Arsenal in 1885, and inspector of stores in 1888. He was promoted major in 1892, and from 1899 to 1912 was superintendent of the Royal Gun Factory. From 1907 to 1912 he held in addition the appointment of superintendent of the Royal Carriage Factory. He was made a C.B. in 1911, and retired from the Army in 1912, 4 years after attaining the rank of colonel. On the outbreak of War in 1914 he was appointed assistant director of mechanical transport at the War Office, becoming director of mechanical transport at the Ministry of Munitions in 1916. In recognition of his achievements as an inventor of artillery instruments and electrical apparatus he was elected a Fellow of the Royal Society in 1895. He served on the Board of the National Physical Laboratory from 1907 to 1911, and was made a K.C.B. in 1916. Elected an Associate of The Institution in 1883, he became a Member in 1888, and served on the Council from 1901 to 1904 and from 1905 to 1907, also as a Vice-President from 1907 to 1910. His paper on "The Applications of Electricity in the Royal Gun Factory, Woolwich Arsenal" was read before The Institution in 1905.

EDWARD MASSEY HOLLINGSWORTH was born at Garston, near Liverpool, on the 22nd June, 1870, and died at St. Helens, Lancashire, on the 27th February, 1937. He served his time with Messrs. Robinson and Cook, engineers and ironfounders, of St. Helens, and later received his technical education at the Manchester School of Technology, where he obtained in 1895 the bronze medal award of the City and Guilds of London Institute in mechanical engineering.

He first became known to the writer of this notice in 1898; he was then chief draughtsman to the St. Helens Corporation Gas Department. When the writer was appointed chief engineer to the Corporation Electricity Department Hollingsworth became his principal assistant. There were few wiremen in those days, and classes were therefore started at the local technical school, the Gamble Institute, for training wiremen and jointers. At those classes Hollingsworth lectured on mechanics.

He revelled in diverse sorts of engineering, and without doubt he had at St. Helens an ample field in which to exercise his skill. A first-class designer, he never hesitated to tackle any problem—large or small, easy or difficult.

There was at the works at that time a watchman by the name of Pilkington, an old man who could recite Shakespeare at length with great eloquence, and the writer remembers many happy evenings with him and Hollingsworth and others, the delight of which consisted in good company and literary talk, often combined with intense discussion on technical matters.

When the writer left St. Helens, in 1903, Hollingsworth was appointed chief electrical engineer, a position which he held until the end of 1918. During the War years he was coal controller for the South-West Lancashire area.

He first came into contact with the United Alkali Co., Widnes, in connection with the supply of electricity in bulk to their Hardshaw Brook (St. Helens) works. In October, 1918, the company made him their chief electrical engineer, and he became responsible for the electrical work of all branches of the firm up and down the country, with headquarters at the West Bank power station, Widnes, which was then being built. The capacity of this station, originally 11 000 kW, he increased in 1924 to 25 000 kW, and it became one of the most economical in the country.

He continued with Imperial Chemical Industries, Ltd., after the amalgamation, until his retirement in December, 1934. During the previous three years he was mainly engaged on extensive reorganization and development of power supply at the Castner-Kellner Alkali Co., Runcorn. After his retirement he was actively engaged in consulting work on behalf of firms in various parts of the country.

He was greatly interested in hospital work and in the application of electricity thereto; at the time of his death he was engaged in superintending the erection and equipment of a new X-ray block in the Providence Free Hospital, St. Helens, of which institution he had been vice-chairman for 25 years.

He joined The Institution as an Associate Member in 1902, became a Member in 1912, and in the same year was elected to the Committee of the Manchester Local Section (now the North-Western Centre). He served on the Committee of the Mersey and North Wales (Liverpool) Centre from 1919 to 1932, being Chairman for the session 1923–24.

Hollingsworth had a very strongly developed artistic side to his mind. He was a very fair artist, and made beautiful water-colour drawings; in later years he took to oil with reasonable success. He had read well and wisely, and talked most interestingly on many subjects. He was a man with the most delightful disposition, was absolutely firm in his convictions, and possessed a most

excellent sense of humour, which illuminated his conversation. He was a vivid raconteur and would relate, often in perfect Lancashire dialect, many homely stories about the people he met and liked. A most courteous, kind, and happy man. J. S. H.

ARTHUR GORDON CAHUSAC HOLROYDE was born on the 5th July, 1892, and died in October, 1936. He was educated at Sidcup College and at the City and Guilds Engineering College, South Kensington. After serving 3 years' apprenticeship with the Lancashire Dynamo and Motor Co. at Trafford Park he was appointed, in 1916, assistant superintendent of the furnace room at the Dolgarrog works of the Aluminium Corporation, becoming superintendent 3 years later. He then served as an assistant on the staff of Messrs. Heap and Digby, consulting engineers, Westminster, and subsequently as a junior partner in the firm. In September, 1926, he was appointed construction engineer by the Departmental Government of Caldas, Colombia, and was engaged on the construction of hydro-electric power plants and aerial ropeways. Three years later he became chief engineer of Las Empresas Unidas de Occidente and was responsible for the operation and construction of the hydro-electric power plants, coffee mills, and river steamers of that company. He was elected an Associate Member of The Institution in 1921 and a Member in 1930.

RICHARD JOHN HUGHES, who was well known in submarine cable circles, died on the 16th February, 1937. He was born in London in 1860, but spent his early years at Liverpool, where he was educated. He entered the telegraph service of the Post Office some years after the private companies had been taken over. He subsequently joined the Direct United States Cable Co. and served at Ballinskelligs, Ireland, and at Torbay, Nova Scotia.

Some years later he returned to England and, after a short period of service with the Eastern Telegraph Co. in London and at Porthcurno, became one of the original staff of the newly formed Commercial Cable Co., taking up duties at Canso, Nova Scotia, some months before the service was opened to the public. In 1900 he was appointed first superintendent of the company's station in the Azores and devoted 4 years to establishing that international cable junction. He collaborated at this time in some early experiments on the first successful system of automatic relaying of signals received over long cables. He was always convinced that automatic retransmission of signals was desirable and could be accomplished, and he gave every encouragement to workers in that field.

In 1904 he became superintendent of the Commercial Cable Co.'s station at Waterville, Ireland, at a time of rapid expansion and keen competition between the Atlantic cable companies. It was during this period that the adoption of a means of amplifying the received signals at the end of long submarine cables resulted in a great increase in operating speeds; and one of the first "magnifiers" put into normal service was installed at Waterville. He remained at Waterville, which during the War years was one of the busiest cable stations in the world, until 1919 when he became manager in England for the same company and, later, manager of plant, also director of several associated companies. The last considerable expansion of the company's activities took place during his term of office in London, namely the laying of the 1923 Atlantic cable. This period also witnessed the final accomplishment of satisfactory automatic relaying of cable signals. He retired from the company in 1930.

He was elected an Associate of The Institution in 1898, an Associate Member in 1899, and a Member in 1905.

FREDERICK HENRY JACKSON was born in 1863 and died in 1937. He received his technical education at King's College School, and his practical knowledge with Messrs. Willans and Robinson. Whilst with that firm he went with Col. Crompton to Vienna and assisted him in the first lighting of that city by electricity; he also met Major-General Webber who, when he became engineer to the City of London Electric Lighting Co., asked him in 1891 to become his assistant. He retired from the service of that company in 1930.

During his early connection with the company's Bankside station he appreciated that if engines were to be run condensing, taking their supply of condensing water from the river, it would be necessary to provide some means of straining the water, and in co-operation with the late Mr. Frank Bailey he devised the type of rotary strainer which is now in use in many parts of the world.

From a very early age he was a "river man," and, from rowing and motor-boat cruising in the early days, he later turned his attention to sailing. He designed and sailed his own boats, which were all named "Caprice," and he was rated by many as one of the most capable helmsmen on the river. He was elected a Member of The Institution in 1899. E. H.

DAVID EARDLEY McLAREN, who died at Adelaide on the 21st December, 1936, was born at Calcutta in 1877. He was educated in this country at Bedford Grammar School and Bedford Technical School. He then went to New Zealand and, a year later, to Adelaide, where he studied at the university. From 1901 to 1904 he held an appointment with Messrs. J. A. Newton and Co., Melbourne. Shortly afterwards he founded the firm known as Newton, McLaren, Ltd., subsequently becoming chairman of the company and, in 1935, managing director. He was elected an Associate of The Institution in 1899, an Associate Member in 1903, and a Member in 1910, and he served for several years on the South Australia Local Committee.

PROFESSOR MAGNUS MACLEAN, D.Sc., LL.D., J.P., F.R.S.E., died on the 2nd September, 1937, in his 80th year. He was born in Skye in 1858 and received his education at the General Assembly School in Colbost, in which he was subsequently a pupil teacher. He entered in 1877 as a Queen's Scholar the Free Church Training College, Glasgow, and at the end of his period of training became a teacher in a school in Sutherlandshire. He then re-entered Glasgow University with a London Highland Society Bursary, obtaining in his career a Lorimer Bursary in mathematics and a Thomson Experimental Scholarship in the physical laboratory attached to the Natural Philosophy Department. His work in the laboratory brought him into close association with Lord

Kelvin, this association continuing for many years, as, after he had graduated with honours in mathematics and natural philosophy, he was appointed Lord Kelvin's chief assistant. In 1892 he was appointed lecturer in physics to medical students, and 3 years later became lecturer in pure and applied electricity to the engineering students of the university. In recognition of the notable research work which he had carried out during this time and communicated in several papers to learned societies, the university conferred on him the degree of D.Sc., and he was elected a Fellow of the Royal Society of Edinburgh.

The chair of electrical engineering in the Royal Technical College, Glasgow, became vacant in 1899, and Dr. Maclean was appointed to this position, which he held with distinction for 25 years. He acted as examiner in experimental physics at Edinburgh University, and held office in many scientific and educational societies in Glasgow. In 1903 he was appointed a member of the Moseley Commission on Education, and with it visited the United States.

As "a leader and first-rank authority in electrical science and distinguished alike in Gaelic language and literature," Glasgow University conferred the degree of LL.D. upon him in 1919. He was the author of important works on "Modern Electric Practice," "Physical Units," "Exercises on Natural Philosophy," and "Exercises on Electrical Engineering."

He retired from the chair of electrical engineering in 1923 on reaching the age limit of the Scottish Education Department. He was, for a period, chairman of the Craigpark Electric Cable Co.

He was elected a Member of The Institution in 1899, and was a strong supporter of the Scottish Centre in all its activities. He was Chairman of the Centre in the session 1901–1902, and for the second time in 1925–1926. In the interim his connection with the Committee was almost continuous. His was an outstanding personality and he will be remembered with affection by all who knew him. R. B. Mi.

His Excellency the MARCHESE MARCONI, G.C.V.O., LL.D., D.Sc., died on the 20th July, 1937, at his home in Rome. Born at Bologna on the 25th April, 1874, he was only 63 at the time of his death, but during the last 43 years of his life he had seen wireless grow from an idea—of the practical value of which he alone was originally convinced—into a world-wide means of communication affecting the life of every individual.

Although an Italian by birth, Marconi had Irish and Scottish ancestry, and was as much at home in England and with the English language as he was in Italy and with Italian. His father, Giuseppe, was an Italian country gentleman who, in 1864, married Miss Annie Jameson, daughter of Mr. Andrew Jameson of Daphne Castle, County Wexford, Ireland. The issue of the marriage was two sons, of whom Guglielmo was the younger. He was educated privately at Bologna, Florence, and Leghorn. As a boy he took a keen interest in physical and electrical science. In 1895 the idea became firmly rooted in his mind that a system of telegraphy through space could be provided by means of electric waves, the existence of which had been foreseen mathematically by Clerk Maxwell in 1864 and, later, investigated experimentally by Heinrich Hertz, Oliver Lodge, Righi, and others. Interesting scientific experiments had been carried out in London and elsewhere with these electric waves, but Marconi was the first to devise the practical means by which they could be made to provide a new and revolutionary method of telegraphic communication.

In the early summer of 1895 he conducted a number of experiments at his father's country house at Pontecchio, near Bologna. These experiments, made with crude and inefficient apparatus, soon began to give results which appeared to him to be remarkable, communication being established in that year over distances in excess of a mile. The first considerable advance which he made was his discovery of the marked effect of the simultaneous use of elevated transmitting and receiving aerials connected to the ground through the generators (transmitters) and detectors (receivers) of electric waves. He discovered that by connecting one of the spheres of the spark-gap by means of a vertical wire to a metal plate buried in the earth, he was able to multiply many times the range of communication for a given amount of power. In his receiver he used a form of coherer, or sensitive detector, employing nickel and silver filings, connected to the earth and to an elevated conductor, in the same way as was done at the transmitting end, and provided with connections to a relay and other mechanical arrangements, which made it capable of receiving and recording the impulses of telegraphic signs transmitted through space from the sending station. In these early days, he also discovered that the distance of communication increased very rapidly if the height above ground of the elevated aerials was increased. This fact was pointed out in his first patent and was also clearly described in a letter dated the 14th November, 1896, addressed by him to Mr. William Preece (afterwards Sir William Preece), engineer-in-chief of the British Post Office.

In 1896 Marconi came to England, and on the 2nd June of that year he took out the first patent ever granted for wireless telegraphy based on the use of electric waves. He continued his experiments in London, and in the same year demonstrated his invention before officials of the Post Office and other representatives of British and foreign Government Departments. These demonstrations were first carried out on the roof of the General Post Office, St. Martin's-le-Grand, London. Later experiments for the Post Office were carried out on Salisbury Plain and across the Bristol Channel from Penarth to Brean Down, near Weston-super-Mare, ranges first of 2 miles, then of 4 miles, and afterwards of 9 miles being obtained.

When the Marconi Co. was formed in July, 1897, the maximum range over which wireless messages had been received was 10 miles, though later in the year a distance of 34 miles was achieved. Persistent research and experiment, in face of not a little opposition and scepticism, brought steadily improved results until the Atlantic was bridged in 1901, and the whole Empire linked by a chain of wireless beam stations in 1928.

During this period numerous improvements embodied in patents taken out by Marconi were utilized. On the 26th April, 1900, he applied for a patent for "tuned or syntonic telegraphy as well as multiplex telegraphy with a single aerial." The important novelty was the incor-

poration of tuned closed with tuned open circuits in both the transmitter and receiver. This patent, the number of which was 7777, became famous in the history of wireless, and its validity was upheld in the High Court by a decision of Mr. Justice Parker.

The successful transmission and reception of a signal across the Atlantic Ocean from Poldhu in Cornwall to St. John's, Newfoundland, on the 12th December, 1901, confirmed his opinion that electric waves would not be stopped by the curvature of the earth and therefore could be made to travel any distance separating any two places on our planet, a view he had held for many years in the face of considerable opposition. The wireless conquest of the Atlantic may be regarded as the culminating point of his pioneer work.

In 1902 Marconi, during a voyage on the American liner S.S. "Philadelphia," received messages up to a distance of 700 miles by day and 2 000 miles by night, thus first discovering the now well-known fact that wireless signals can usually be received over much greater distances at night than during the hours of daylight. In the same year he designed and patented a practical form of magnetic detector based on the effect of electrical waves on iron or steel when subjected to a varying magnetic field. This magnetic receiver replaced the receivers up till then in use, and for over 10 years remained the standard receiver on the great majority of sea-going vessels equipped with wireless.

In 1905 he took out his patents for the horizontal directional aerial, which marked an advance in the design of long-distance stations. During the same year, in a lecture delivered before the Royal Institution, he first pointed out that most probably wireless transmissions right round the world to places near the antipodes would be carried out with greater ease and with less expenditure of electrical energy than would be necessary to much nearer places. Later results fully confirmed the correctness of these views. In 1910, assisted by Mr. H. J. Round, he received signals and messages at Buenos Aires from Clifden (Ireland) over a distance of about 6 000 miles. In 1912 he devised a new method for generating continuous waves, commonly known as "the timed spark system." This system was employed for several years at many important long-distance stations and, by its means, he sent the first messages ever transmitted by wireless from England to Australia on the 22nd September, 1918.

In 1916, during the Great War, he commenced experiments in Italy with very short waves, with the object of devising a directive, or beam, system of wireless telegraphy for war purposes. This was a principle on which he had also worked during his earliest experiments, but work on these lines had been put on one side in favour of the use of longer and longer waves combined with higher power. Later, in England, with the assistance of Mr. C. S. Franklin, important results were obtained by the use of 15-metre waves between London and Birmingham. The result of tests with short waves, between 15 and 60 metres, carried out in 1916 and 1922 was fully described in papers by Marconi and Franklin in 1922, and these short, directed waves made possible the establishment of direct wireless telegraph services between England and the Dominions and India between 1926 and 1928. At the time of his death he was engaged in experiments with micro-waves, in the conviction that they could be turned to commercial uses.

The value of his work has been recognized by Governments, universities, and learned societies all over the world. In 1914 he was nominated by the King of Italy to be a member of the Italian Senate, and in June, 1929, was created a hereditary marquis by the King of Italy. In January, 1928, he was appointed President of the Italian National Council of Research, and on the 29th November, 1930, he became President of the Italian Royal Academy and Member of the Council of the Fascist Party. On the 12th February, 1931, he was appointed by His Holiness the Pope to be a member of the Pontifical Academy of Sciences.

He was elected a Member of The Institution in 1898, and an Honorary Member in 1926, and he served on the Council from 1903 to 1906. The first scientific paper which he read in this country was that before The Institution on the 2nd March, 1899, entitled "Wireless Telegraphy," for which he was awarded the Fahie Premium.

W. G. R.

Professor THOMAS MATHER, F.R.S., who died on the 23rd June, 1937, was born in 1856 at Higher Walton, near Preston, and served an apprenticeship with Messrs. Thomas Whittaker and Sons, millwrights and engineers, Higher Walton, and with Messrs. Joseph Clayton and Sons, engineers and boilermakers, Preston. He attended science classes in Preston from 1875 to 1878 and in the latter year headed the list of Whitworth Scholars. He then went to Owens College, Manchester, where he was awarded the Ashbury Scholarship and the Engineering Certificate with Honours in Mathematics and Engineering. In 1881 he headed the list of Royal Exhibitioners and proceeded to the College of Science, South Kensington, where he spent one session. In 1882 he was appointed assistant to Prof. Ayrton, an association which lasted until Prof. Ayrton's death in 1908, when he succeeded him as Professor of Electrical Engineering at the Central Technical College. He retired in 1922, being accorded the title of Emeritus Professor. He was elected a Fellow of the Physical Society in 1887 and of the Royal Society in 1902.

He joined The Institution as an Associate in 1890, became an Associate Member in 1902 and a Member in 1908, and served on the Council and on various Committees. He was for many years a member of the Board of Agriculture Committee on Electroculture.

When he joined Prof. Ayrton in 1882, electrical measurements were in their infancy, and the types of measuring instruments then in use were those now associated with museums. Prof. Mather was associated therefore with the development of modern electrical measuring instruments from their early beginnings, and no one had a more intimate knowledge of the difficulties which were met with, or took a more active part in overcoming them.

His first paper read before the Physical Society in 1885 dealt with "Calibrating a Galvanometer with Constant Current." A paper on the design of galvanometers was published jointly with Ayrton and Sumpner in 1890; and papers on the same subject followed in 1896 and 1898.

The outcome of this work was the well-known Ayrton–Mather type of moving-coil instrument with its narrow shuttle-shaped coil. Papers were also contributed in 1897 to the *Electrical Review* on "The Sensibility of Galvanometers," and to the British Association on "Short versus Long Period Galvanometers for Very Sensitive Zero Tests."

The Ayrton–Mather universal shunt was invented in 1894 and was described in a paper read before The Institution; in 1897 they read a joint paper before The British Association on "The Use of a Constant Total Current Shunt with Ballistic Galvanometers."

In 1892, in conjunction with Ayrton, he had read a paper before the Physical Society describing the use of an insulated metal strip doubled back on itself as a non-inductive resistance, and in 1905 he and Duddell introduced the gauze resistance in which the silk-covered wire is woven into a warp of silk threads in such a way that the effects of inductance and capacitance are approximately neutralized.

To many people the names of Ayrton and Mather suggest electrostatic voltmeters, a subject to which they devoted much thought and careful experiment. They developed a range of instruments, including a suspended reflecting voltmeter giving a full-scale deflection with 10 volts, and in a paper read before The Institution in 1894 they described the coating of the glass cover of voltmeters with a transparent conducting film to prevent errors due to electrification. Another joint paper to the British Association in 1895 was on "The Back E.M.F. and True Resistance of the Electric Arc." This subject was followed up by their brilliant research student Duddell and led to his discovery of the singing arc.

In 1895 Ayrton and Mather described before the British Association the magnetic field tester in which a coil is rapidly rotated through 180° by pressing a trigger, and in 1900 before the Physical Society they read a paper on "Price's Guard Wire in Insulation Tests."

In 1907 an epoch-making paper in the history of electric units was read before the Royal Society by Ayrton, Mather, and F. E. Smith, entitled "A New Current Weigher and a Determination of the E.M.F. of the Normal Weston Cadmium Cell." This was followed in 1908 by a paper on "Silver Voltmeters" by Mather, Smith, and Lowry. In conjunction with Duddell, Prof. Mather developed the Duddell–Mather wattmeter.

Shortly before Prof. Ayrton's death in 1908 Prof. Mather undertook to rewrite and extend "Practical Electricity." This he did with such characteristic thoroughness that it was not completed until the beginning of 1911. In conjunction with the writer of this notice he also published a book on "Exercises in Electrical Engineering."

His influence on those around him, both staff and students, was very marked; his excessive modesty, his kindliness and gentle courtesy, his meticulous care in everything he did, his punctuality and his high ideals of conduct, reacted unconsciously on all who were fortunate enough to be closely associated with him. G. W. O. H.

CHARLES WOODWARD NEELE was born on the 15th December, 1866, and died on the 3rd April, 1936. Educated at Reigate Grammar School and at Merchant Taylors' School, London, he studied electrical engineering at evening classes at the Polytechnic Institute, Regent-street, London, and at Owens College, Manchester. In March, 1883, he became a pupil at the Lambeth works of the Anglo-American Brush Electric Light Corporation, and a year later entered the telegraph and electrical department of the London and North-Western Railway as an apprentice. He subsequently became assistant electrical inspector of the London district of the railway, and, later, electrical inspector of the Rugby and Central district. His next promotion was to works manager of the electrical department workshops, in which capacity he supervised the manufacture of electrical apparatus. In August, 1898, he was appointed chief electrical engineer of the Great Central Railway. He undertook the supervision of the erection and equipment of the power houses for the Great Central line to London which was then being laid down, and he was also in charge of all the power and lighting installations and electrical communications. On the amalgamation of the British railways he became chief electrical engineer of the Great Central Section of the London and North-Eastern Railway, from which position he retired in 1924. After his retirement he served for 3 years as electrical engineering consultant to the railway. He was elected a Student of The Institution in 1886, an Associate in 1889, and a Member in 1913.

FREDERIK CARL C. NIELSEN died on the 14th January, 1937. He was born in Copenhagen on the 21st May, 1851, and joined the Great Northern Telegraph Co. in 1870. After a few months' training in England he was transferred to the East and served at Shanghai, Amoy, and Nagasaki. In 1875 he was appointed principal of the agency in Yokohama. In 1877 he was promoted to station superintendent at Amoy, and later at Hong Kong. From 1878 to 1883 he served as secretary to the managing director at the head office at Copenhagen. He was then placed in charge of the London office. In 1891 he became general manager of the company, a position which he held until his retirement on the 1st July, 1915, during which period he played an important part in the development of the company, showing exceptional skill in all its negotiations, his great technical, political, and linguistic knowledge being of particular assistance in this connection. He joined The Institution as a Foreign Member in 1875, and was elected a Member in 1911.

DAVID THOMAS POWELL, youngest son of the late G. H. Powell, J.P., of Hampstead, died on the 29th December, 1936, at the age of 65. He was trained as an electrical engineer at the Central Technical College, South Kensington, and subsequently served an apprenticeship with Messrs. Hawthorne, Leslie and Co. at Hebburn-on-Tyne, remaining with this firm in the drawing office. In 1897 he joined the staff of the Kensington and Brompton Electricity Co., and in 1898 the staff of Sir Alexander Kennedy (then Prof. Kennedy). He remained in the firm of Messrs. Kennedy and Jenkin and subsequently those of Messrs. Kennedy and Donkin and Mr. S. B. Donkin, until his death, throughout this period of 38 years being engaged in a large number of schemes connected with the supply and distribution of electricity.

He was resident engineer for the erection of the whole of the Grove Road generating station for the Central Electric Co., and was also in charge of all the cable distribution-system from that station to the stations of the Westminster Co. and the St. James's and Pall Mall Co. He was also responsible for the erection of the plant in the substations, and he carried out the work in connection with all the extensions of the Grove Road generating station and of the transmission and substation system.

He was largely responsible for the design and contract works in connection with the Portobello power station of the Edinburgh Corporation and was the chief resident engineer in charge of the erection of this station, together with the whole of the transmission system from it to a system of new substations in Edinburgh, including the equipment in these substations. On the completion of this work he became responsible in the London office for contract work generally. For the last 9 or 10 years of his life he was engaged almost entirely on work for the Central Electricity Board and was particularly responsible for the Central Scotland scheme.

His charm of character and his ability and judgment were very much esteemed by his colleagues and by contractors' engineers. The contracts for which he was responsible were always carried out to satisfactory and harmonious conclusions, and his manner in settling difficulties between the client, the consulting engineers, and the contractor, was an example to all concerned and will remain in their memory as one of his great qualities. He joined The Institution as a Student in 1892, and was elected an Associate in 1895 and a Member in 1913.

S. B. D.

JOHN ROBERTS, first borough electrical engineer of Durban, Natal, died on the 1st June, 1937, at the age of 64. He was born in Montrose, Scotland, on the 15th December, 1872, and was educated in London. He served his apprenticeship with the Electric Construction Co. at Wolverhampton, and was sent by that firm at the age of 24 to superintend the erection of the first electrical generating plant installed by the Durban municipality. On the completion of the work he was invited by the Town Council to become borough electrical engineer, and entered upon his duties in February, 1898. He held office until his retirement on reaching the age of 60 in December, 1932, but continued to serve as local manager of the Congella (Durban) undertaking of the Electricity Supply Commission until the end of February, 1937. He had taken office early in the history of the Commission, the station having been put into service to provide a bulk supply to the Durban municipality in November, 1928.

Mr. Roberts occupied a prominent position among municipal electrical engineers, perhaps the greatest achievement of his life's work being the remarkable degree to which he extended the use of electricity in the domestic field, bringing Durban to the forefront of the world's cities in this respect. This work was started on a limited scale by the introduction—despite considerable opposition—of the two-rate tariff known as the "Norwich" system, which has since been adopted with certain amendments in most of the larger centres of South Africa. In the industrial field he was also very successful in developing the adoption of electricity, in this case also largely due to the introduction of low tariffs. He was a strong protagonist of railway electrification, and had he lived a few months longer he would have had the satisfaction of seeing the whole of the Natal main lines under electric operation.

Under Mr. Roberts's guidance the supply mains were extended in 1914 beyond the boundaries of the town (as it was known until its elevation in 1935 to the rank of "city"), and one suburb after another was electrified until to-day the mains extend approximately 20 miles in three different directions, while the total sales of electricity for all purposes reached in July, 1937, a figure of over 168 million units per annum. These suburban extensions entailed an increase in the transmission pressure from the original figure of 2 750 volts, single-phase a.c., by increasing stages up to the present-day maximum of 33 000 volts, 3-phase, 50 periods.

In 1924, when wireless broadcasting was in its infancy, he induced the Durban Corporation to establish the first municipally-owned broadcasting station in the world; this was taken over a few years later by the African Broadcasting Co.

He was elected a Member of The Institution in 1922.

J. H. G.

ROBERT KNIGHT ROBERTSON, who died on the 24th August, 1937, at the age of 54, was the son of a well-known Dunfermline merchant. He was educated at Dunfermline High School, Lauder Technical School (Dunfermline), Alloa Academy, and Fife Mining School and Engineering College. He acted as a lecturer for some 4 years in the last-mentioned institution. His practical training comprised an apprenticeship in mechanical engineering with a Dunfermline firm of linen manufacturers, and in electrical engineering with the British Electric Plant Co., Alloa.

In 1905 he was appointed assistant constructional engineer with Messrs. Bruce Peebles and Co., and was engaged on the construction of works and buildings for the Fife Electric Power Co. and the Scottish Central Electric Power Co. In 1906 he joined the Fife Electric Power Co. as senior shift engineer, with which company he remained until his death. From 1910 to 1917 he was employed on distribution and mains work. From 1917 to 1919 he was in charge of the test department, and from 1919 to 1929 was chief technical assistant, when he took up his final position of chief engineer. He had a fine character and personality. Those who knew him had the greatest admiration for his wide technical knowledge and his grasp of the problems of rural electrification.

He was elected an Associate Member of The Institution in 1917 and a Member in 1925, and he served on the Committee of the Scottish Centre in 1927–28 and 1933–36, taking a great interest in all its activities. R. B. Mi.

The Right Hon. Lord RUTHERFORD of Nelson, O.M., F.R.S., was born at Nelson, New Zealand, on the 30th August, 1871, and died on the 19th October, 1937. His untimely death at the early age of 66 removes from us the outstanding experimental scientist of the age. For nearly 40 years he had directed a physical laboratory,

first at McGill University, Montreal; then in Manchester; and finally for 18 years in Cambridge. For almost the whole of that long period, coterminous with what Rutherford himself described as the heroic age in physics, his laboratory, whichever it might be, was the resort of physicists from all over the world, and played the leading part in the development of our knowledge of atoms and the atomic structure of matter.

Seldom can anyone have started his career at a moment more auspicious, for Rutherford entered Cambridge as an advanced student in 1895, within a year or two of the discoveries of X-rays by Röntgen, of radioactivity by Becquerel, and of the electron by J. J. Thomson. Seldom can anyone have been better endowed to grasp, or more gloriously successful in exploiting, the opportunities that crowded fast upon him.

Ideally equipped for directing a physical laboratory, he was capable at once of intense sustained individual research, of suggesting and inspiring with his own fire cognate researches of others over a very wide field, and, particularly in later years, of organizing the team work required for elaborate attacks on many modern problems. His genial but dominant personality, his exacting demands for the best, the inspiration of his personal research, and the generosity with which he suggested and directed the work of his staff and students, created an atmosphere in any laboratory he directed which no one who experienced it will forget, or, alas, ever hope to meet again.

The three periods of his professorships, in Montreal, Manchester, and Cambridge, correspond roughly with the three major phases of the development of atomic theory which will always be associated with his name. The first, at Montreal, was concerned with unravelling the intricate phenomena of radioactive change and the chemistry of the natural radioactive elements. For this work Rutherford received the Nobel Prize for chemistry in 1908, and it remained to the end a good joke against him, which he thoroughly appreciated, that he was thereby branded for all time as a chemist and no true physicist. The second, at Manchester, is associated mainly with the discovery of the nucleus and the development of the nuclear model of the atom—once called the Rutherford–Bohr atom, and now so universally accepted that it is just " the atom," the shortened title being perhaps the greatest compliment that scientists can ever pay to a scientific theory. The third, at Cambridge, was devoted to the study of the structure of the nucleus itself, developing from the disintegrations of nitrogen by α-particles, which were first observed by Rutherford himself at the end of his Manchester period. The third period culminated perhaps in 1932, that *annus mirabilis* of nuclear physics, which saw the discovery of artificial disintegration by protons, of the positron and of the neutron, the first and third being Cavendish contributions, while other members of the laboratory took an important share in the work of placing that strange entity the positron securely on the map. During this period, Rutherford was as much engaged in direction of the large-scale operations of the laboratory as in personal research of his own, and was highly excited and delighted by the laboratory's triumphs. The last few years were rather years of reconstruction and preparation for a new attack with still more powerful weapons on nuclear problems. Rutherford's own fire seemed unabated to the end.

This is not the place to enter in further detail into his achievements or the achievements of his laboratories in experimental physics. We may more suitably turn to another side of his activities—his interest in electrical engineering, and beyond that in the general relationship of science and industry, which was a matter of intense interest to him for the last 10 years or more of his life. In a general way, one may say that his connection with electrical engineering was always close, for in almost all his work he was using electrical methods. But the connection was certainly closest at the beginning and end of his career. His first work, started before he came to England, was on the development of a magnetic detector of electromagnetic waves, and at one time he held the long-distance record for wireless telegraphy (about 2 miles). Much later he returned to the engineering field, round about 1927, when the attack on nuclear problems was being held up for lack of sufficient variety and power in the available projectiles. He then foresaw the need for very high-voltage discharge tubes, and organized experiments on the development of high-voltage apparatus of a type within the reach of the modest pocket of a university laboratory. This was a pure problem of electrical engineering, which culminated, as is well known, in the disintegration of lithium by protons in 1932. Somewhat earlier he had also taken great interest in the engineering problems of Kapitza's successful projects for the production of intense magnetic fields. From among his many other honours we may record here that The Institution of Electrical Engineers invited him to deliver the 13th Kelvin Lecture before them in 1922, which was entitled " Electricity and Matter," and they awarded him the Faraday Medal in 1930.

In 1930, in addition to all his other activities, he undertook the Chairmanship of the Advisory Committee of the Department of Scientific and Industrial Research, and in that capacity performed much work of the greatest national service. He held strongly that organized research, either in the private research laboratory of a single firm, or in the co-operative research association of a group, was essential to the success of modern industry. His great reserves of common sense, the quickness of his appreciation of essentials, and the strength of his dominating personality, made him an ideal person for this post, and he took the keenest delight in watching and fostering the rapid growth to successful maturity of the Research Associations brought into being with the Department's help.

This illustrates one side of the picture, the help that science gives to industry, but there is another side, of which Rutherford was equally appreciative—the help that industry gives to science. Much of the recent work of physical laboratories has only been rendered possible by the use of amplifying devices, whose component parts at least were developed industrially to meet the needs of broadcasting and other wireless services, and could hardly have been developed so far and so fast in any other way. It gave Rutherford the greatest pleasure to recall the contrast between the

laborious counting by eye of his earlier experiments and the recent counting practice of his laboratory, in which apparatus constructed out of amplifying circuits and bits of dismantled totalizators and telephone exchanges would count more sensitively and accurately and more than 100 times as fast.

He lies buried in Westminster Abbey in the physicists' corner of the nave, by the memorials to Faraday and to Maxwell, and the graves of Kelvin and of Newton. We mourn him indeed, with the whole scientific world, but with this one small comfort that we shall never see him growing old. R. H. F.

EDWARD ALAN SHRIMPTON died on the 3rd June, 1937, at Wellington, N.Z. He was born on the 22nd March, 1869, and, after serving as a telegraphist, was transferred to the engineering branch of the Post and Telegraph Department in May, 1899. In 1908 he was promoted to be assistant telegraph engineer at Christchurch, N.Z., being transferred to a similar position in Auckland during the following year. He served there for 2 years, and then went to Wellington as telegraph engineer for the Wellington district. In June, 1918, he became chief telegraph engineer for New Zealand, a position which he held until his retirement in March, 1926. During his service to the Government he installed at Timaru the first central-battery telephone system in New Zealand, and he was also responsible for the introduction into New Zealand of the Murray multiplex telegraph printing machine. After his retirement he was employed as consulting engineer in the New Zealand office of Standard Telephones and Cables, Ltd. He was elected an Associate Member of The Institution in 1909, and a Member in 1912.

ARTHUR MOLYNEUX SILLAR was born in London in 1865, and died on the 6th March, 1937. After being educated at Shrewsbury School, he joined in 1882 the Jablochkoff Electric Light and Power Co. and was in charge of the company's electric lighting installation at the Health and Inventions Exhibitions in 1884–1885. In 1887 he became assistant engineer of the United Electrical Engineering Co. and, in 1890, was appointed chief engineer of the Electrical Engineering Corporation.

In 1894 he entered into partnership with Mr. E. M. Lacey in private practice as Messrs. Lacey and Sillar (subsequently Messrs. Lacey, Sillar, and Leigh). When the partnership was dissolved in 1912 Mr. Sillar continued in private practice on his own account at Westminster.

During the period 1894–1912 his firm acted for, amongst others, the municipalities of Batley, Belfast, Blackburn, Bournemouth, Brighouse, Bury, Colchester, Colwyn Bay, Farnworth, Middleton, Radcliffe, Rawtenstall, Rochdale, Salford, Swindon, and Tynemouth, in connection with the design and construction of electricity generating stations, electricity distribution systems for power and lighting, and the electrification of tramways, the latter aggregating some 300 miles of track. They also prepared the schemes and parliamentary plans for the Lancashire Electric Power Co. and the Yorkshire Electric Power Co., and supervised the erection of the first power station of the Lancashire Electric Power Co. at Outwood, near Radcliffe; also the design and erection of some 30 miles of overhead transmission mains for the same company. In this connection it may be interesting to mention that the Lancashire Electric Power Co. was one of the first, if not the first, of the large supply undertakings in this country to adopt and install turbo-driven alternators for what has since become the standard system of 3-phase 50-period generation and supply.

His firm were also retained 1900–1902 by the Great Central Railway Co. in connection with the electricity generating stations at Marylebone, Leicester, and Nottingham, and by the London and North-Western Railway Co. on the design and erection of their electrically-driven hydraulic plant at London Road, Manchester.

During the War Mr. Sillar was engaged on Government work, and since the War on important schemes in this country and the Far East. He was retained as a witness on various important arbitrations and in some cases acted as arbitrator.

It may properly be claimed that he was one of our early pioneers of electricity supply, of whom but few survive him. He will also be remembered socially by many as one who took a leading part in the initiation and successful continuance of the Electrical Engineers' Ball.

He was elected an Associate of The Institution in 1887, and a Member in 1895. E. M. L.

JOHN KENDALL STOTHERT died at Sidmouth on the 17th October, 1937. Born at Swansea on the 31st January, 1861, he was the second son of the late Rev. S. K. Stothert, M.A., D.C.L., a naval chaplain who served through the Crimean War and saw much active service. He received his general education at Retford School and Cambridge University, and entered Faraday House early in 1891, remaining until 1893. During his time there, he greatly distinguished himself, being bracketed Head Prizeman of his year, and finally served as a premium apprentice with the London Electric Supply Corporation at their Deptford station.

On leaving in 1893, he assisted in the erection of the generating station of the Liverpool Overhead Railway, under the late Mr. Thomas Parker, and on the completion of this work joined the staff of Messrs. John Fowler and Co., of Leeds. During his engagement with them, he supervised a large portion of the work they carried out at the Blackpool, Burton-on-Trent, Coventry, Newport, Reading, and Islington electricity supply stations.

In November, 1897, he became assistant manager of the London office of Messrs. Babcock and Wilcox, but resigned in October, 1899, at his uncle's urgent request, to undertake the management of the shipyard and engineering works of Messrs. G. K. Stothert and Co., of Bristol, owned by his uncle. In October, 1901, he rejoined Messrs. Babcock and Wilcox, and was appointed manager of their Glasgow office, a position which he held with distinction until his retirement. For some years he was a director of the Clyde Valley Electrical Power Co., and of the Strathclyde Electric Supply Co.

A sufferer for many years from asthma and bronchitis, he found the Glasgow climate, in winter, too trying, and on doctor's advice he retired in April, 1920, and went to live in Sidmouth, where he resided until his death.

He joined The Institution as a Student in 1891, and was elected an Associate in the same year and a Member in 1912; and he was Chairman of the Scottish Centre in 1916–17. He was also President of the Faraday House Old Students' Association in 1912.

He was a good example of the real old English gentleman; his geniality and kindliness were spontaneous. Few men had a larger circle of friends, and he will always be affectionately remembered by all who knew him.

H. W. K.

JOHN EDWARD TAPPER was born in March, 1876, and died on the 16th August, 1937, at the age of 61. He was educated at the Philological School, Marylebone, at that time affiliated with King's College, and he subsequently spent a few years in commercial life. He then turned his attention to electrical engineering and was for some years in charge of various private generating plants, meantime pursuing his studies in evening classes at Regent Street Polytechnic. In 1899 he joined the staff of the Brighton Corporation Electricity Department. When the Beckenham electricity supply was inaugurated by the British Insulated Cable Co. as lessees for the Beckenham Urban District Council, he was appointed chief assistant, and, in 1904, chief engineer, later becoming chief electrical engineer and manager to the Council when the latter took over the undertaking from the company. This position he held continuously until his death.

Mr. Tapper was an indefatigable worker and had many outside activities. He was the London secretary of the Associated Municipal Electrical Engineers for many years, and at his death held the positions of president, secretary, and treasurer, of the London section of that Association. He served for a time on the I.M.E.A. Council and represented that Association on a number of B.S.I. and other sub-committees. He also served on a number of E.D.A. committees. He was a member of the Area 10 Whitley Council for the electricity supply industry, representing the employers' side. He was also a member of the Conference of Local Authority Undertakers of Greater London from its inception, and rendered much valuable though unobtrusive service in that capacity. The word "unobtrusive" eminently fits his character. His unassuming manner, coupled with his capacity for hard work, endeared him to all with whom he came in contact. Perhaps this is best expressed by the words of the chairman of his committee at the council meeting following his death. They were these: "He positively detested self-advertisement, but if he could hear any complimentary remark paid about his staff he was extremely appreciative." He was elected an Associate Member of The Institution in 1903 and a Member in 1912.

W. C. P. T.

JOSEPH TAYLOR, honorary secretary of the Scottish Centre of The Institution, died on the 30th January, 1937, at the age of 70. He received his early training at the Albany Academy, Glasgow, and started his business career in the employment of Messrs. Walter Macfarlane and Co., ironfounders. After a short time with this firm, he was appointed agent in Glasgow for the Edison Swan Electric Co., and for 46 years was that firm's manager for Scotland, retiring about 3 years ago. In that capacity he did splendid pioneering work in the early days of the industry, when the use of electricity was being introduced into the country.

He was, perhaps, best known to many as the devoted honorary secretary of the Scottish Centre of The Institution, a post which he held for over 23 years. He was personally known to all the members of the Centre. No details of the increasing and varied work escaped his consideration, and in the burdensome tasks of organizing three very memorable and successful Summer Meetings he fully earned the respect and esteem of the whole Institution. His tact and exceptional charm remain a pleasant and inspiring recollection to all who have been impressed by his kindly individuality.

He was elected an Associate of The Institution in 1900, an Associate Member in 1905, and a Member in 1918.

R. B. Mi.

JOHN HAROLD THOMPSON was born at Seaham Harbour, Durham, in 1879, and was educated at Elmfield College, York, and at the University of Adelaide, South Australia. He served his apprenticeship with Messrs. Ellis and Clarke, of Adelaide. In 1898 he came to this country and was successively mains assistant at Liverpool, engineer-in-charge at Dewsbury, and assistant engineer at Burton-on-Trent. In 1908 he was appointed station superintendent at Carlisle, becoming in the following year chief assistant. He left Carlisle in 1919 on his appointment as chief engineer and manager of the Colne Corporation Electricity Department, a position he held up to the time of his death, which occurred on the 8th April, 1937. He was of a kindly and genial disposition, and his sudden passing was deeply felt by his many friends and colleagues. He joined The Institution as an Associate Member in 1907, and was elected a Member in 1921.

R. W. G.

ELIHU THOMSON, D.Sc., who was elected an Honorary Member of The Institution in 1904 and was a Past-President of the American Institute of Electrical Engineers, died at his home at Swampscott, Mass., U.S.A., on the 13th March, 1937. Born in Manchester on the 29th March, 1853, he emigrated with his parents in 1858 to Philadelphia, Pa., where he was educated at the public schools and at the Central High School. While still a child he devoted much time to the construction of electrical apparatus and to astronomy, a hobby which he continued to pursue in later life. On leaving school he worked for some months as an analyst at a chemical factory, before returning to the High School as a teacher of chemistry. There he remained for 10 years, leaving in 1880 to join the American Electric Co. in company with E. J. Houston, one of his colleagues on the staff of the High School. In 1883, Thomson and his associates purchased the controlling interest in the firm, which was renamed the Thomson-Houston Co. This concern was in 1892 merged with the Edison General Electric Co. under the name of the General Electric Co. (America), and Thomson became consulting engineer and director of the research laboratories at Lynn. He was closely associated with the company until his death.

Of his numerous achievements in the field of electrical research one of the earliest was the successful experiment in wireless signalling which he carried out in 1875.

About 1879 he produced his 3-coil dynamo with automatic regulator which was successful in maintaining constant regulation of a system of many arc lights, irrespective of the number of arcs connected. This invention was based on his earlier discovery that the resistance of the arc varies inversely as the current passing. In 1881 he produced his magnetically-operated lightning arrester, embodying the important principle now employed in magnetic blow-out switches. He was the first to notice the force of repulsion exerted on a copper ring when placed near an electromagnet excited by alternating current, an effect which he applied in the form of the repulsion motor. Of particular importance among the many other electrical inventions which stand to his credit are the high-frequency dynamo, the art of resistance electric welding, the constant-current transformer, the induction regulator, and various improvements in X-ray tubes. In recognition of his outstanding scientific work he was awarded the Hughes Medal of the Royal Society (in 1916), the Kelvin Medal (in 1924), and the Faraday Medal of The Institution (in 1927).

JAMES ALEXANDER V. THOMSON died on the 6th June, 1937. He was educated at Watson's College and George Heriot's School, Edinburgh, and had his technical training at the Heriot-Watt College in that city. He served his apprenticeship with an Edinburgh firm of engineers, and in 1899 entered the service of the Edinburgh Corporation Electricity Department, afterwards transferring to the Aberdeen Electricity Department, where he served, later, as resident engineer and clerk of works at the new station then in process of erection. He held this position until December, 1913, when he was appointed chief mechanical and electrical engineer to the British Aluminium Co., Kinlochleven, which position he held until his death. His duties covered a wide area: he had charge of the lay-out and maintenance of new plant, including light and heavy mill machinery and electric furnaces, the complete supervision of the repair workshops, the power house staff, and the maintenance of the running plant in the power house, together with the high-pressure pipe track. He was elected an Associate Member of The Institution in 1910 and a Member in 1923. R. B. Mi.

GEORGE ARTHUR WEBB died at Port Elizabeth on the 6th January, 1937, at the age of 60. He left England about 1900 and proceeded to Capetown and thence to Natal, but the fascination of the Witwatersrand goldfields attracted him to Johannesburg, where he took up a post with the Porges Randfontein in 1903. He was identified with several Rand Mines' companies, among which were the Nourse Mines, Ltd., Geldenhuis Deep, Ltd., and Durban Roodepoort Deep, Ltd., on which he performed valuable work and successfully surmounted the many difficult problems which confronted electrical engineers in the earlier days on the Rand goldfields.

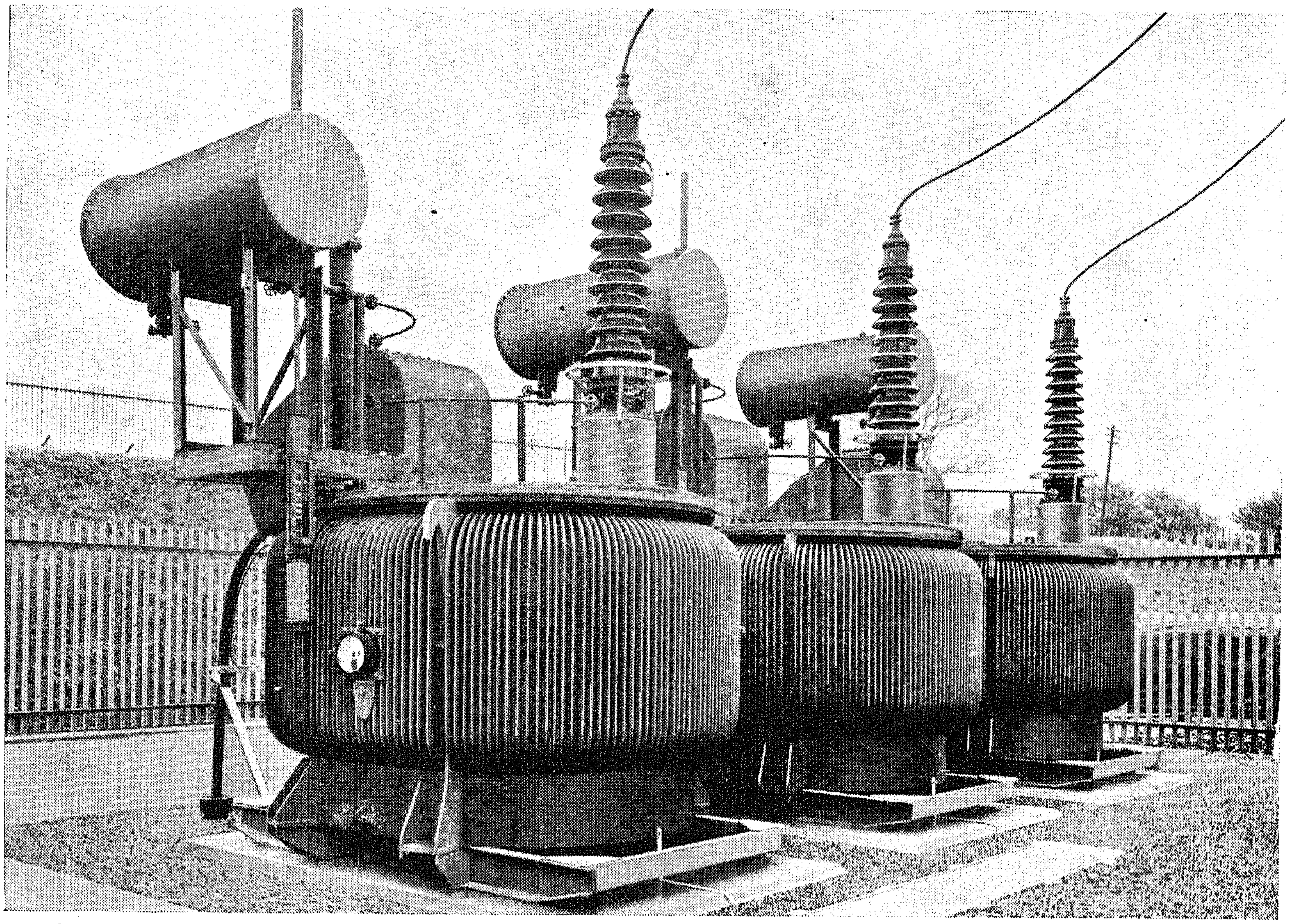
He patented an eccentric truck rope haulage grip which is used successfully in the Witwatersrand fields. Later he went into business at Port Elizabeth, on which he was still engaged at the time of his death.

He was elected an Associate of The Institution in 1902 and a Member in 1919. On the launching of the South African Institute of Electrical Engineers in Johannesburg in June, 1909, he was appointed to the executive and proved himself a valued member for many years on the various sub-committees. He was very well known on the Rand and was of a genial disposition, possessing a fund of humour. W. E.-D.

JOHN HARRY WILD, whose death occurred on the 26th May, 1937, was born on the 17th June, 1878, and served his apprenticeship with the General Electric Co. at the Peel Works, Salford. During his apprenticeship he attended evening classes at the Manchester and Salford Technical Schools and subsequently at Owens College, Manchester. After spending 2 years as superintendent in the electrical department of Messrs. James Scott and Co. at Oldham, he obtained an appointment in 1899 in the testing department of the Lancashire Dynamo and Motor Co., later becoming in 1901 chief assistant engineer, in 1907 assistant general manager, and in 1915 works manager of the company.

In 1916 he was appointed to the staff of Vickers, Ltd., as assistant superintendent of electrical manufactures, leaving in 1921 to join the board of Messrs. Nathan and Allen, with whom he remained until his death. He was a highly trained engineer with a wide experience in the manufacture of all types of electrical machinery, and he carried out many large electrical contracts for the equipment of mills, factories, and hydro-electric and steam-driven power stations. He also travelled extensively overseas, where he had many friends. He was elected an Associate Member of The Institution in 1905 and a Member in 1913. O. H. K.

HENRY WILSON was born on the 12th July, 1867, and died on the 25th December, 1936. He entered the Post Office as a telegraphist at Newcastle-on-Tyne in 1882. In 1892 he was transferred to the engineering department and 4 years later he was placed in charge of the Carmarthen section. When the Post Office started the London telephone scheme in 1902, he was one of the engineers chosen for this work. In 1908 he was appointed staff engineer in the engineer-in-chief's office, and became a member of the Post Office Awards Committee and represented the Post Office on committees of the British Standards Institution. In addition, he was for 20 years lecturer in telegraphy and telephony at Battersea Polytechnic. In April, 1924, he went to South Wales as assistant superintending engineer, and 3 months later he took charge of the district as superintending engineer. He retired in July, 1928, after 46 years' service, and joined the firm of Messrs. Thomas Watson and Son (later absorbed by Hall Telephone Accessories, Ltd.), as consulting engineer, in which capacity his services were greatly valued. He was an active member of the Tyneside Division of Submarine Miners from 1882 until 1892, and this training enabled him to render valuable services during the War when he assisted Colonel (now Sir Thomas) Purves in the design and supply of new signal apparatus for the armies in the field. He joined The Institution as an Associate Member in 1912, and was elected a Member in 1924. A. G. L.



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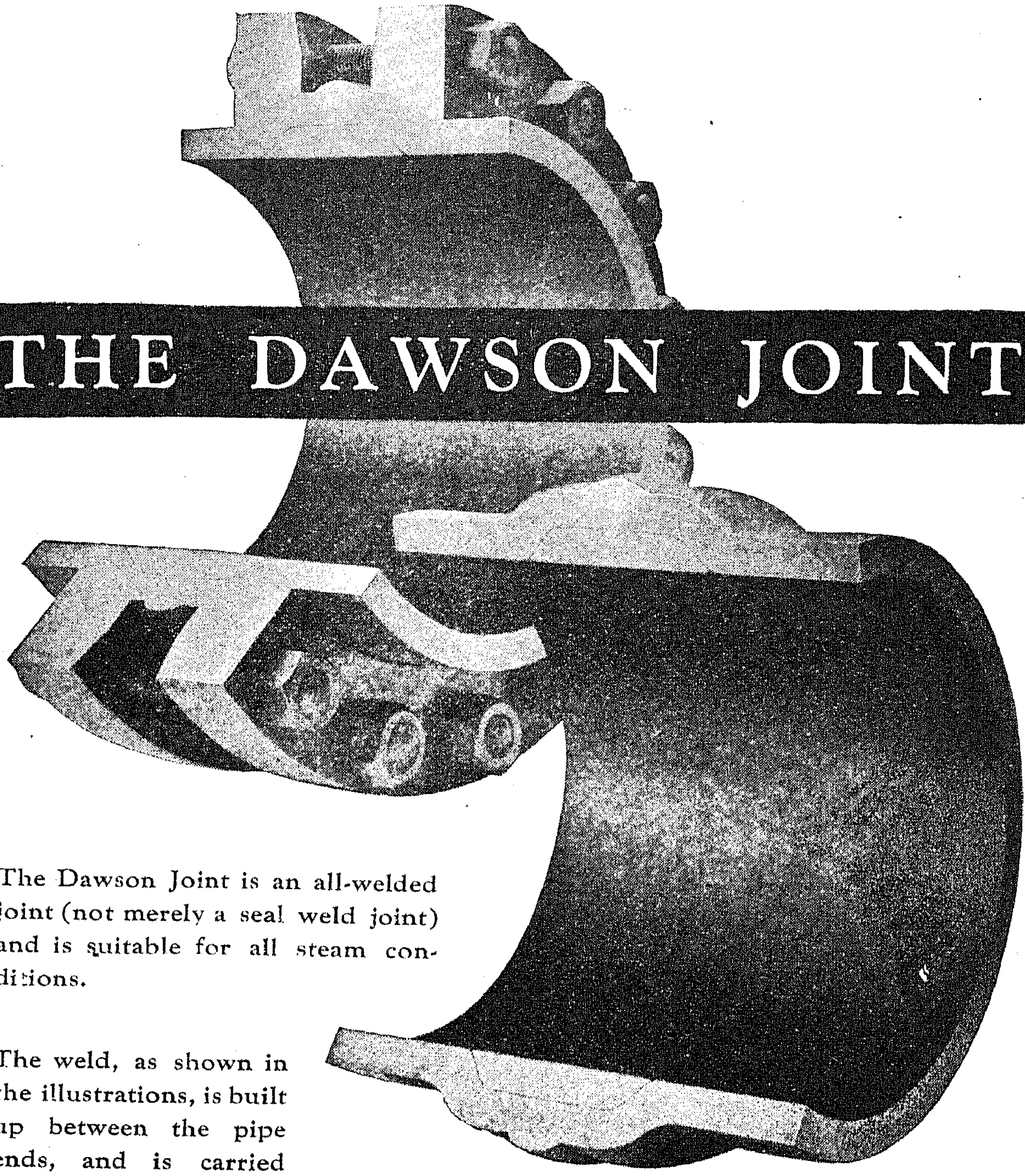

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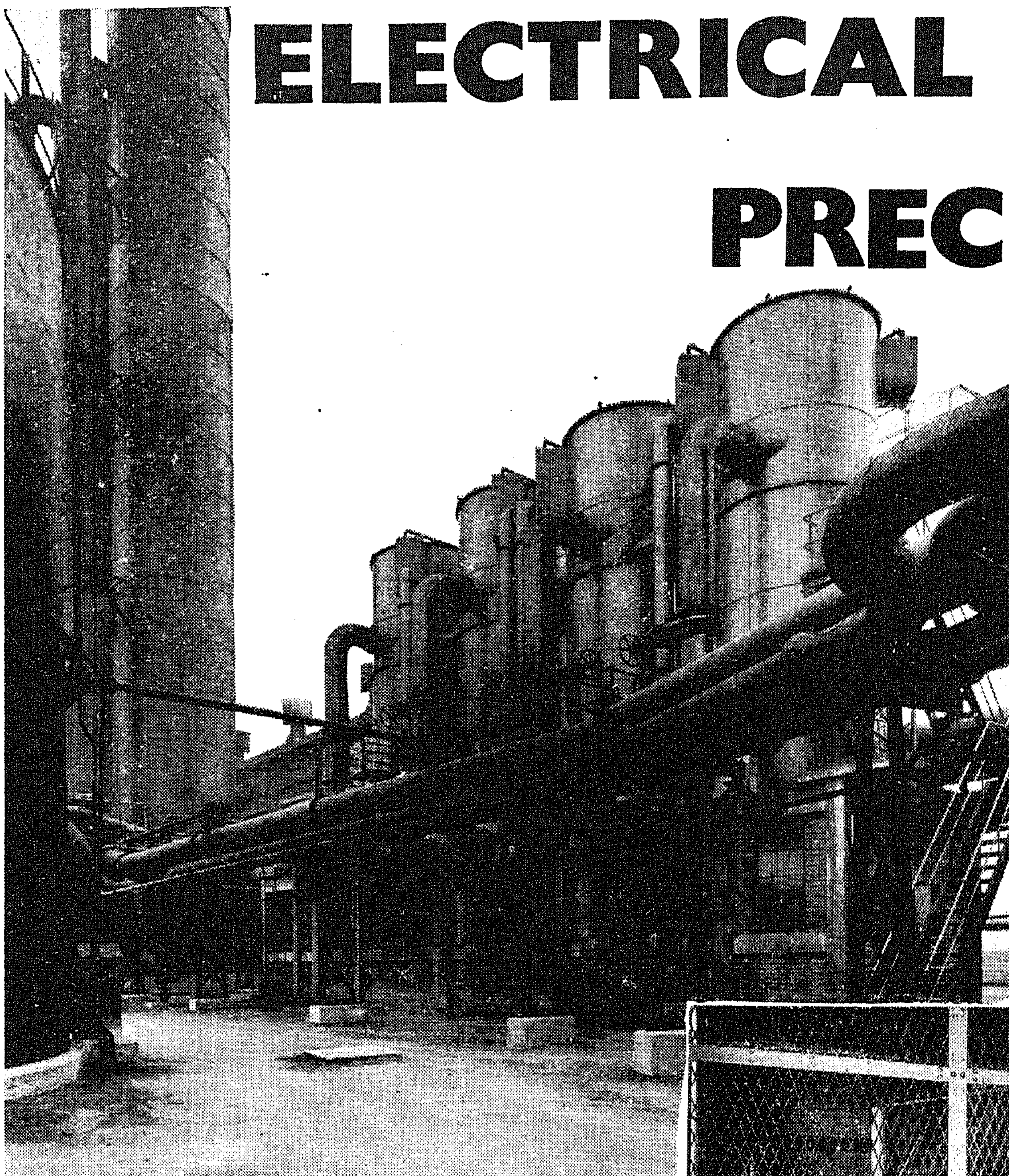

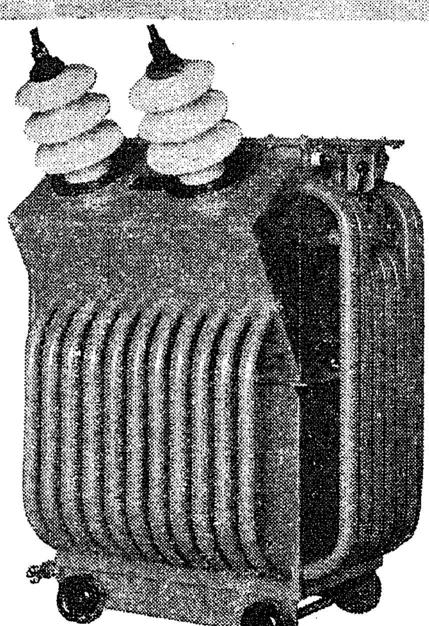

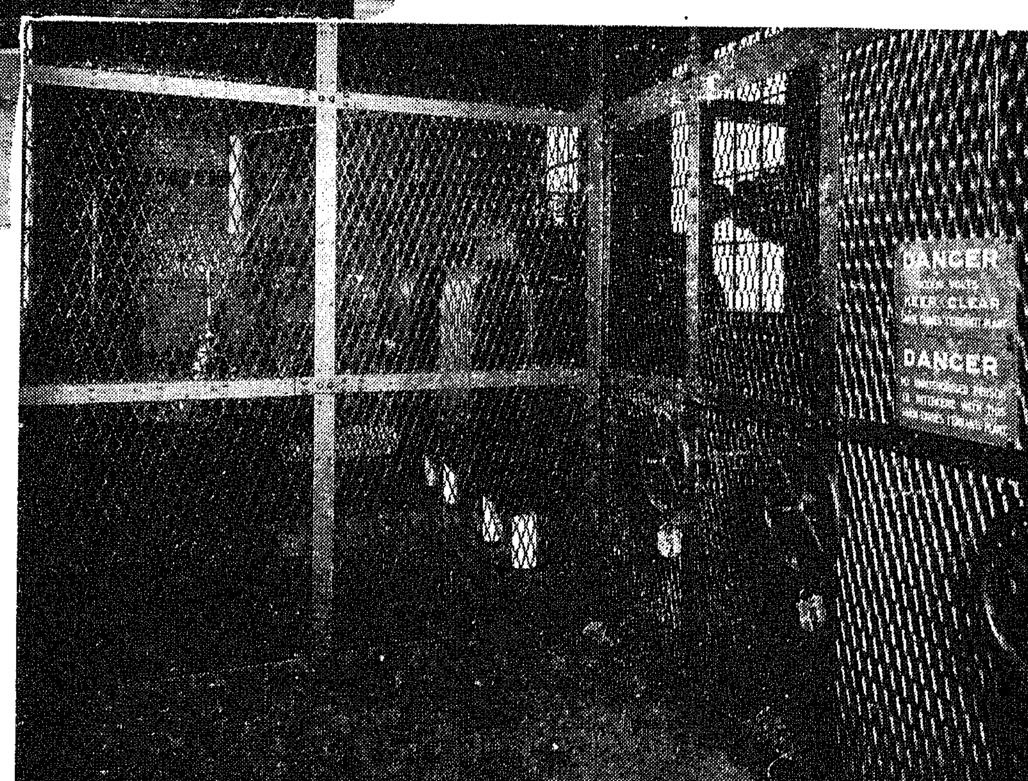
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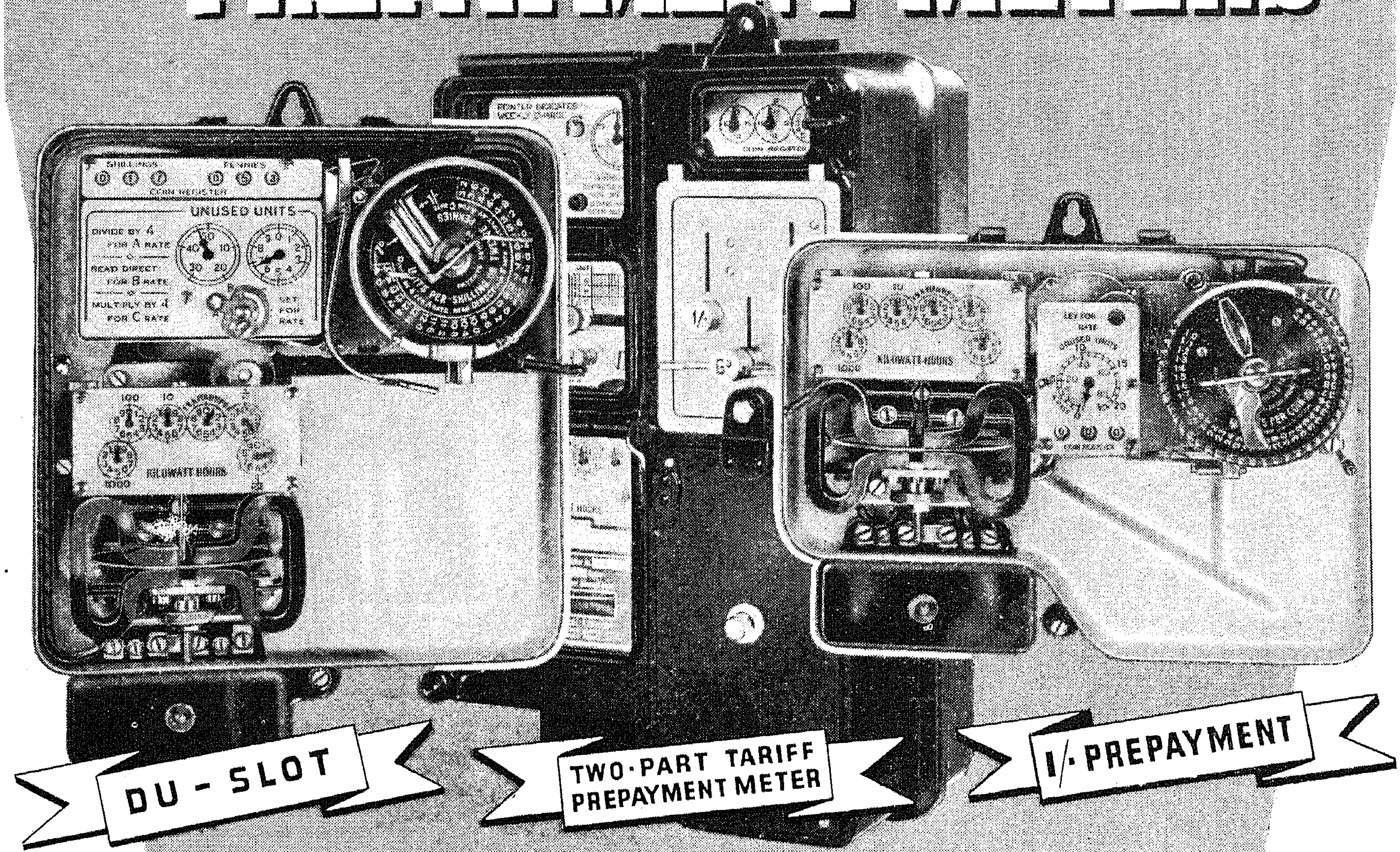

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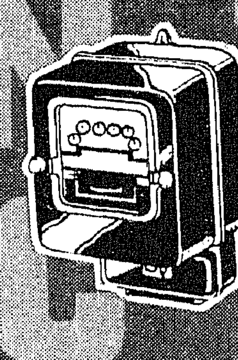

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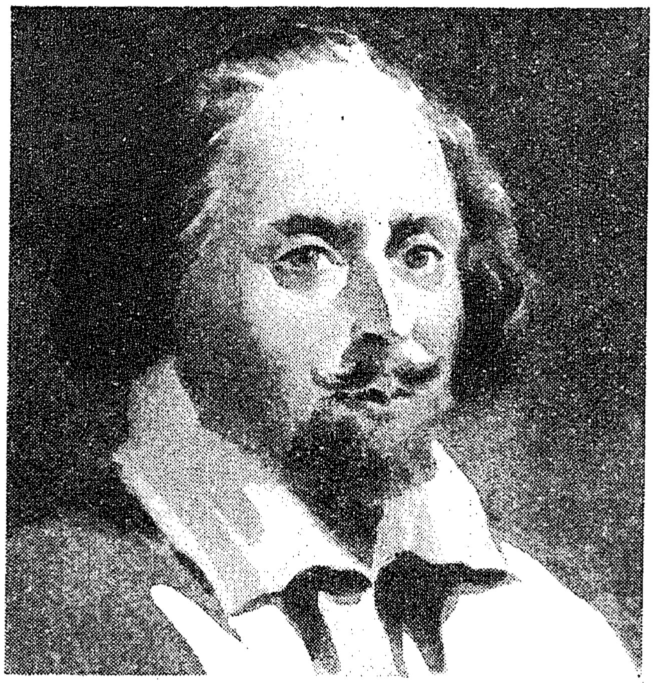

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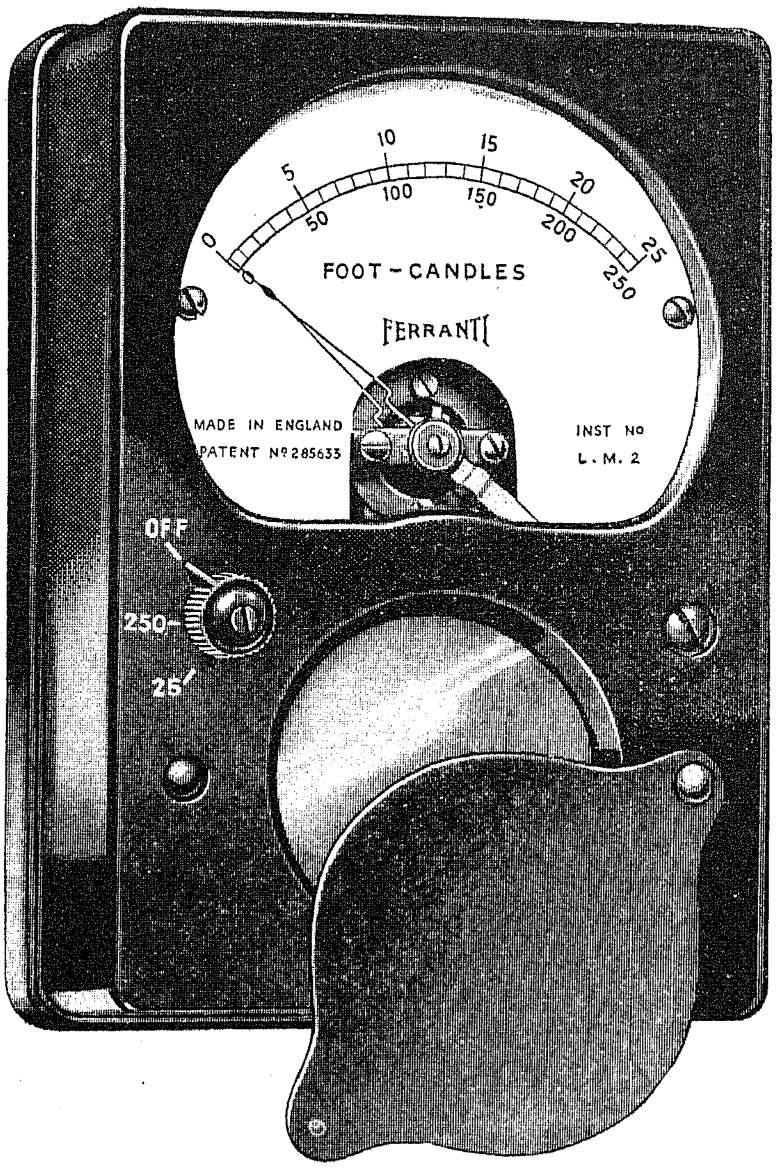

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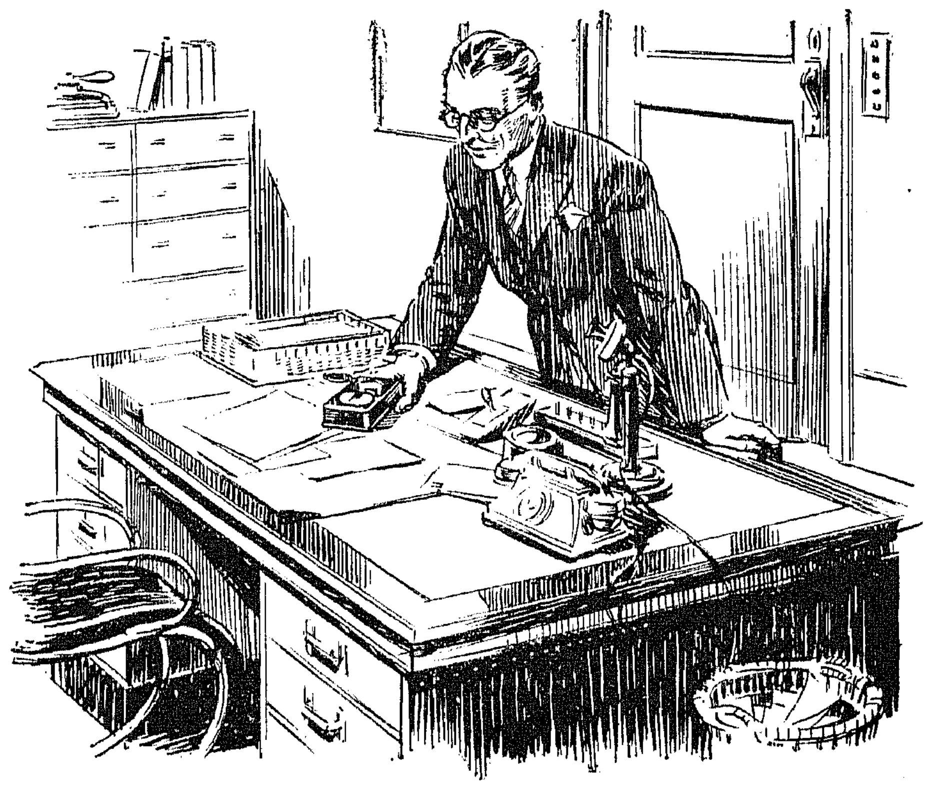

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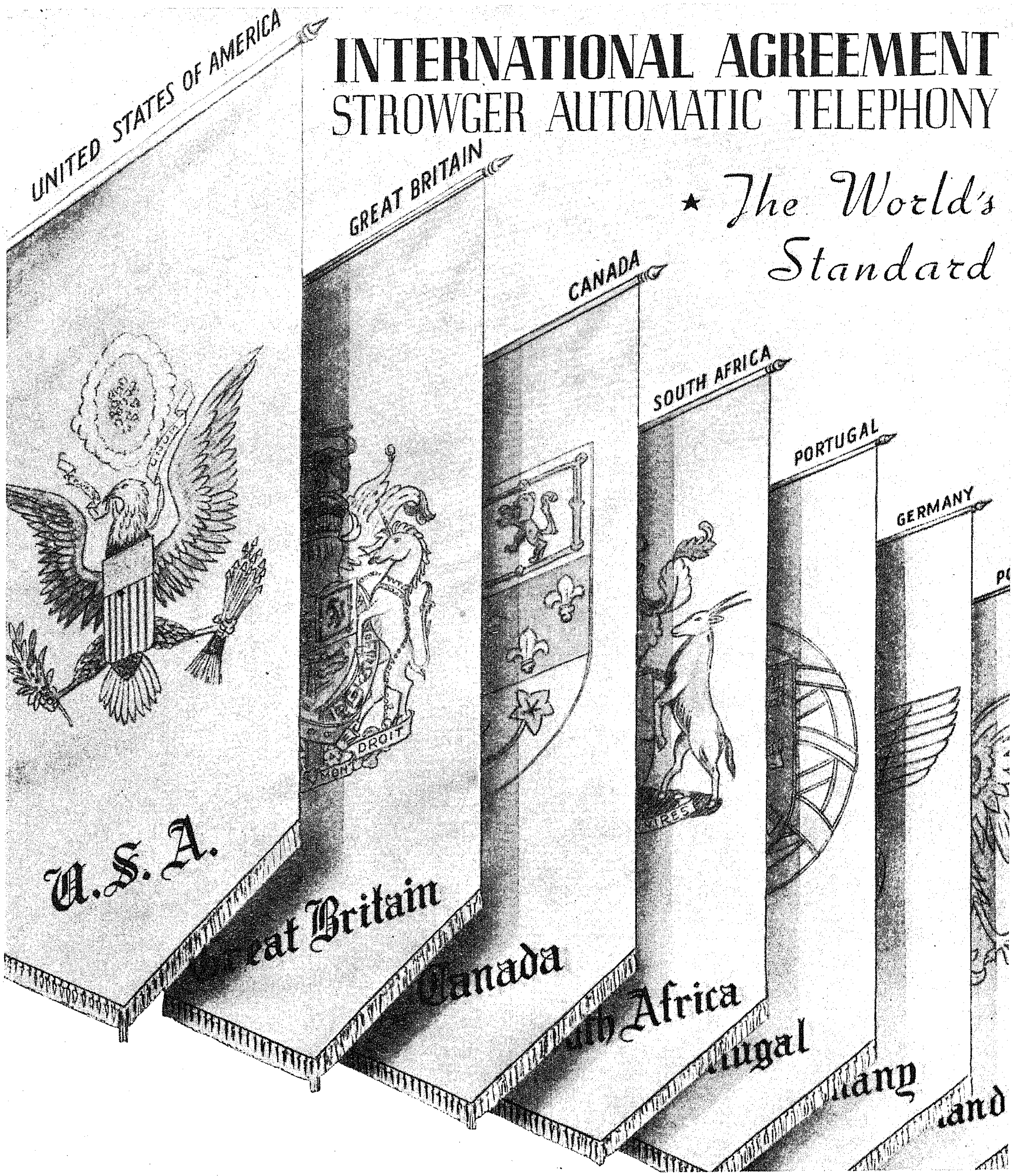

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